NOV 23 1981

1051-H-11

Y3.N88:35/2272

CONTRACTOR REPORT

NUREG/CR-2272
SAND81-7143
AN

Expedient Methods of Respiratory Protection

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Printed November 1981

Prepared for
U. S. NUCLEAR REGULATORY COMMISSION

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EXPEDIENT METHODS OF RESPIRATORY PROTECTION

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Final Report
30 June 1981

Sandia Project Officer: Dr. David C. Aldrich

Prepared for

Sandia National Laboratories
Albuquerque, New Mexico 87185
operated by
Sandia Corporation
for the
U. S. Department of Energy

Work performed under Sandia Contract No.

Funded by
Division of Risk Analysis
Office of Nuclear Regulatory Research
U. S. Nuclear Regulatory Commission
Washington, DC 20555
Under Memorandum of Understanding DOE 40-550-75
NRC FIN No. A1042

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ABSTRACT

Readily-available cotton fabrics (sheet, shirt, handkerchief, and toweling materials) and an inexpensive disposable face mask (3M Corporation, #8710, NIOSH-approved) were tested for their ability to filter aerosol, gas (K_r) and vapors (I_2, CH_3I), species expected to be emitted in the event of a major nuclear reactor accident. For much of the particle diameter range (0.4 μm to 5 μm) tested, the fabrics and the face mask would decrease the particle concentration by a factor of ten or more (ignoring possible leakage around the seal to the face) when operated at a pressure drop deemed acceptable for breathing comfort (100 Pa) and at filtration velocities appropriate to a face mask ($\approx$ 1.5 cm/s). The disposable face mask and the towel performed best on the aerosols. The towel performed even better wet than it did dry. The fabrics showed a retention capability for Kr that was not much less than that of charcoal, offering some protection to users. Dry fabrics were ineffective in removing iodine, but sheeting or toweling wetted either with water or with a baking soda solution would provide a factor of ten or greater reduction in I_2 concentration for the wearer (ignoring possible leakage around the face seal). Although the fabrics averaged some reduction in CH_3I, this was not statistically significant. The experimental results and the associated theoretical analysis are interpreted in terms of the quality factor, the negative reciprocal of the pressure drop times the logarithm of the penetration, quite useful for comparing filter materials under different conditions. A computer program is presented for interpreting/predicting fabric penetration. This work is to be continued in a follow-up study.

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ACKNOWLEDGMENTS

We appreciate the cooperation of Sandia personnel, Gene E. Runkle and especially our project officer, David C. Aldrich. Useful comments were received from our colleagues at the School; from Herb Decker of Ft. Detrick (Frederick, MD), whose work (Guyton, Decker, Anton, 1959) greatly influenced this investigation; and from James A. Martin of the U. S. Nuclear Regulatory Commission.

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SECTION 1

INTRODUCTION

This report contains experimental and theoretical results of our investigation of the effectiveness of some common materials with respect to filtration of aerosols and vapors and a noble gas. It is expected that the results will be of use in devising effective strategies to limit intake of radionuclides in the event of a nuclear reactor accident. The information should also be useful with regard to expedient respiratory protection in other, non-nuclear, accident circumstances, such as fires.

The principal objectives were to retest some of the fabrics used in studies with human volunteers reported by Guyton, Decker and Anton (1959). The materials chosen were to be tested with respect to their penetration by aerosol particles and by I_2, CH_3I, and Kr (vapors and a noble gas expected to be part of the emissions resulting from certain types of potential nuclear reactor accidents).

EXPERIMENTS WITH HUMAN VOLUNTEERS (GUYTON ET AL.)

Guyton et al. selected eight materials for testing for emergency respiratory protection against aerosol hazards. These are listed in Table 1.1, with the description they supplied.

Volunteers were seated in a test chamber and exposed to an aerosol of the spores of the bacterium bacillus subtilis var. niger (also called "B. globigii"), produced by atomizing a suspension of the spores. "The mass median diameter of particles in this aerosol was 2.1 μ with 95% of the particulates between 1.0 μ and 5.0 μ." (Guyton et al., 1959) The aerosol size distribution was apparently determined from cascade impactor measurements (see Guyton and Lense, 1956). The subjects held between their teeth mouth collectors, cartridges filled with absorbent cotton. The collectors had collection efficiency of 83 percent on this aerosol (presumably higher than that for particles larger than 2 μm in diameter and lower than that for particles between 1 and 2 μm), so the amount of material caught was adjusted by a factor of 1.2 by those investigators. The material to be tested was held by hand over the nose and mouth as a mask. The subjects inhaled through the mouthpieces and exhaled through their noses. Each test lasted five minutes. The subjects were instructed to try to minimize the leakage around the peripheral seal. The efficiency is one minus the penetration. The penetration is the ratio of the aerosol concentration (number of spores per volume of air) downstream from the material, determined from the mouth collectors, to the number concentration upstream from the material, determined from samples taken in the test chamber ambient air.

Table 1.2 is a summary of the results of the experiments. Table 1.2 shows the materials, the number of thicknesses used, the flow resistance (for 10 liters per minute drawn through samples having 12.5

TABLE 1.1. DESCRIPTION OF ITEMS EVALUATED FOR EMERGENCY RESPIRATORY PROTECTION (GUYTON ET AL., 1959)

Item Tested	Description
Handkerchief, cotton, man's	Mercerized white combed fabric, 80 x 10 threads/sq. in. [sic]
Toilet paper	Waldorf Scottissue
Towel, bath	Cotton terry weave Federal Spec. No. DDD-T-551 B Type 2, Class D
Bed sheet, muslin	Pepperell Red Label (fine muslin), 131 threads/sq. in.
Shirt, cotton	Arrow Dart
Handkerchief, cotton, woman's	Cotton lawn fabric, 76/72 threads/ sq. in.
Dress material, cotton	Rondo Percale
Slip, rayon	Barbizon Jaunty Fit, acetate and rayon

TABLE 1.2. RESPIRATORY PROTECTION PROVIDED BY COMMON HOUSEHOLD AND PERSONAL ITEMS (AEROSOLS OF 1-5 MICRONS PARTICLE SIZE)(GUYTON ET AL., 1959)

Item	No. Thicknesses	Resistance* mm. H_2O	No. Observ.	Geom. Mean Eff. %	95% Conf. Limits for Mean	
					Lower %	Upper %
Handkerchief, cotton, man's	16	36	32	94.2	92.6	95.5
Toilet paper	3	13	32	91.4	89.8	92.8
Handkerchief, cotton, man's	8	18	32	88.9	85.5	91.6
Handkerchief, cotton, man's	Crumpled	--	32	88.1	85.1	90.5
Towel bath	2	11	32	85.1	83.3	86.8
Towel bath	1	5	30	73.9	70.7	76.8
Bed sheet, muslin	1	22	32	72.0	68.8	74.9
Towel bath	1(wet)	3	31	70.2	68.0	72.3
Shirt, cotton	1(wet)	>150**	15	65.9	57.9	72.3
Shirt, cotton	2	7	30	65.5	60.8	69.6
Handkerchief, cotton, woman's	4(wet)	84**	32	63.0	57.3	67.9
Handkerchief, cotton, man's	1(wet)	98**	30	62.6	57.0	67.5
Dress material, cotton	1(wet)	180**	31	56.3	49.6	62.0
Handkerchief, cotton, woman's	4	2	32	55.5	52.2	58.7
Slip, rayon	1	6	32	50.0	46.2	53.6
Dress material, cotton	1	5	31	47.6	41.4	53.2
Shirt, cotton	1	3	32	34.6	29.0	39.9
Handkerchief, cotton, man's	1	2	32	27.5	22.0	32.5

* At volumetric flow of 10 liters per minute through 12.5 cm^2 area.

** Resistance obtained when checked immediately after hand-wringing. This resistance began to decrease after about one minute, when the material started to dry.

cm^2 areas), the number of observations, the geometric mean (E_{gm}) of the efficiency measurements (E_i):

$$E_{gm} = (E_1 * E_2 * E_3 \ldots E_n)^{1/n} \qquad (1.1)$$

and the 95% confidence interval limits on the measured means.

Some of the materials had been tested wet; that is, after being saturated and wrung dry. The muslin sheet and the rayon slip were not evaluated this way because "they exhibited intolerable resistance to human breathing." (Guyton et al., 1959) The subjects indicated that the fabrics which had shown resistances higher than 36 mm (in the tests at 10 lpm and 12.5 cm^2) were uncomfortable for breathing and would have limited usefulness. Accumulated moisture would make the toilet paper "tear easily which would preclude its use for any prolonged period of time." (Guyton et al., 1979) They concluded, "Therefore, the use of wet items as respiratory protective expedients appears impractical." This conclusion was based on the resistance of the wet materials to air flow.

The expedients that gave greater than 85 percent efficiency at tolerable levels of flow resistance (according to Guyton et al.) were the handkerchief folded to eight thicknesses and the towel folded into two layers, when either was used dry.

Figure 1.1 has plotted on it the penetrations versus pressure drops as measured for various fabrics by Guyton et al. (excluding a few values with pressure drops greater than 100 mm H_2O). If penetration were inversely proportional to pressure drop, a straight line with a slope of -1 would provide the best fit to the data. The figure does give some support to such a hypothesis. The fabrics which give the lowest penetration at a given pressure drop were the towel and the handkerchiefs. The penetrations for the highly flow-resistant wetted handkerchiefs may have been so high because the volunteers had to create leakage paths to breathe at all. Guyton et al. opined that a pressure drop of 20 mm H_2O was about the upper limit for comfort for most people.

EXPERIENCE WITH HALF-MASK RESPIRATORS

One approach to estimating the amount of leakage to be expected from the seal of the fabric to the face is to review the experience of those using half-mask respirators. Leidel (1979) summarized the work of others in testing half-mask respirators, those which cover nose and mouth and extend under the chin: Leakage through the filter materials was much less than 1%, as was respirator valve leakage, both determined using CaCl aerosols with mass median aerodynamic diameters of 0.7 μm. The distribution of leakages, generally due to leakage around the face seal, is shown in Figure 1.2, from Leidel (1979). The median values ranged between about 0.5% and 0.03% and 90th percentile values

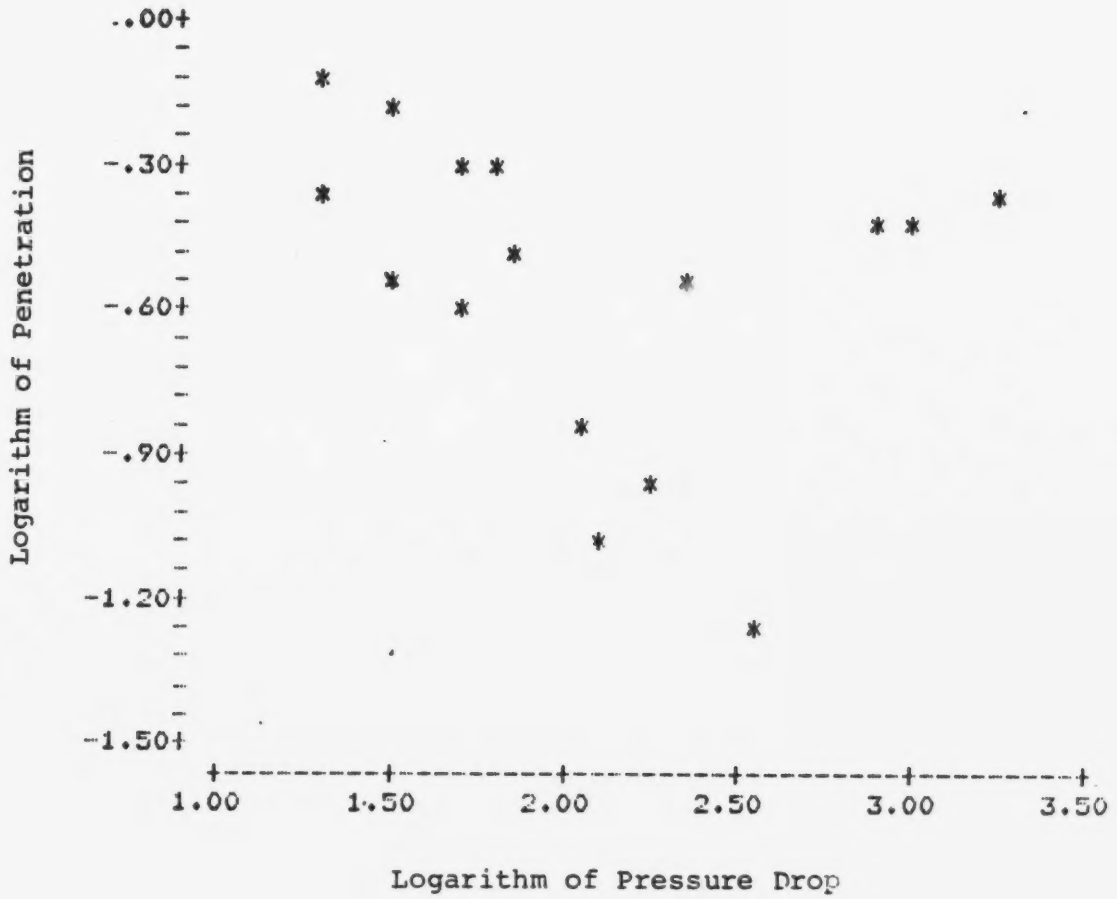

Figure 1.1. Logarithm of penetration versus logarithm of pressure drop (mm H_2O) for fabrics tested by Guyton et al. (1959).

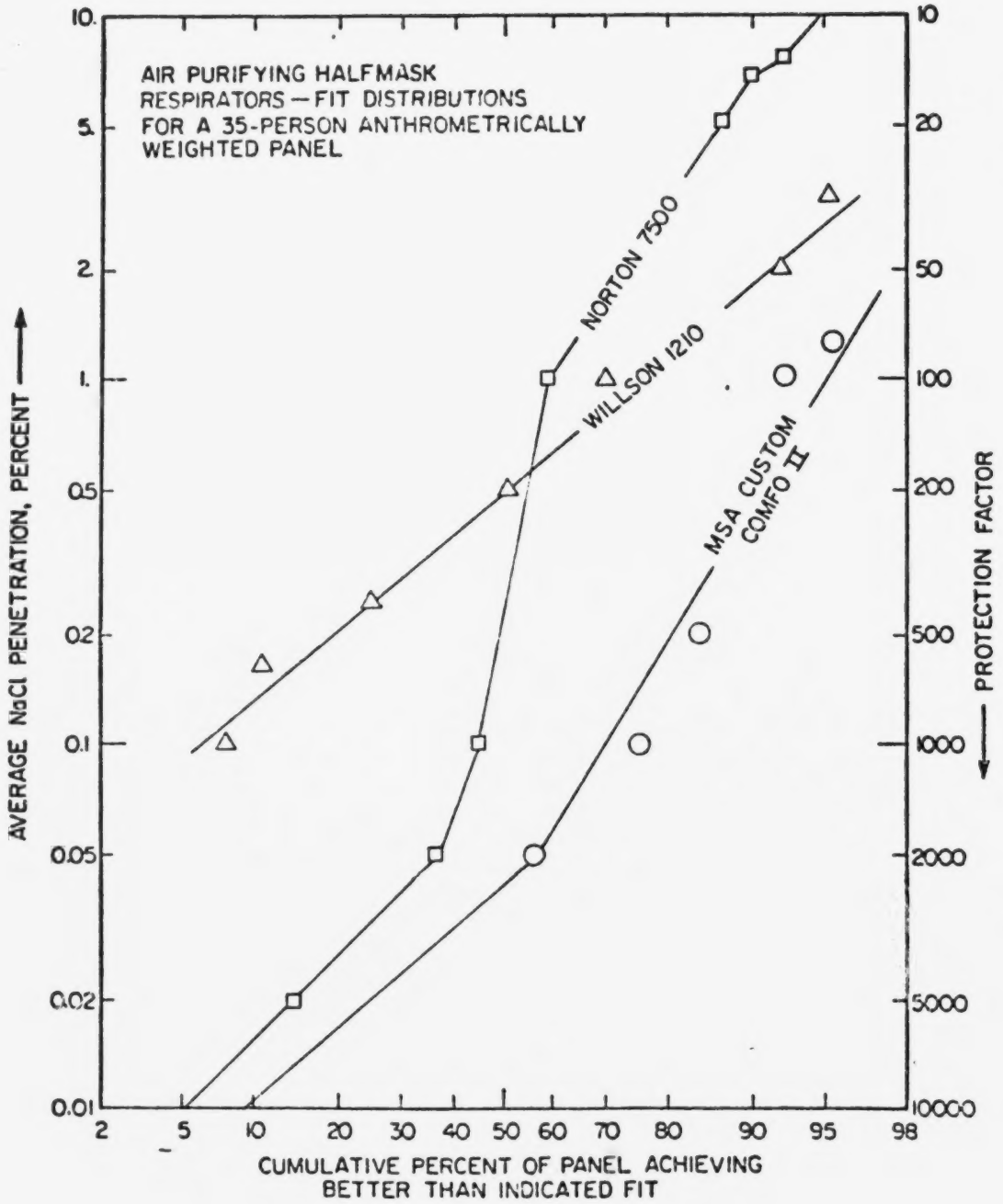

Figure 1.2. Halfmask respirator leakage cumulative distribution functions (Leidel, 1979).

were about ten times these. A few percent or less of an aerosol (such as the NaCl used in the test) or gas would be expected to leak around the seal of material to face, as it is not clear whether such a fabric/skin seal would be better or worse than the seals achieved by the half-mask respirators. This leakage places an upper limit on potential respiratory protection.

SUMMARY AND CONCLUSIONS

The experiments of Guyton *et al.* indicated that expedient respiratory protective measures could provide efficiencies greater than 90% in some instances. Industrial experience with half-mask respirators indicated that leakage around the skin/fabric seal might preclude achieving much better than about 95% efficiency, even if no leakage through the materials occurred. Further, collection efficiency would be expected to vary with respect to aerosol particle size and with gas type. The tests described in this report were designed to extend the information obtained by Guyton *et al.* and by investigations done for industrial respirators, to help determine the potential effectiveness of respiratory protection expedients.

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SECTION 2

EXPERIMENTATION

INTRODUCTION

The prime goal of this project was to re-test materials like those used by Guyton et al. to ascertain their collection efficiencies for aerosol particles and, with lesser emphasis, their efficiencies for I_2 and CH_3I vapors and a noble gas (Kr). It was hoped that our aerosol test results could be combined with those of Guyton et al. to determine not only the penetration of the material, but the penetration plus leakage in use. (As will be explained, this latter goal was not attained.) The aerosol, vapor, and gas tests were similar in that each required the generation of the airborne contaminant and its measurement upstream and downstream from the fabrics that were tested.

AEROSOL TESTS

Experimental Apparatus

To determine the penetration of aerosol through the selected fabrics, the Dynamic Aerosol Test System (DATS) was used. As shown in Figure 2.1, DATS consists of a main test chamber where a supply of filtered air flows past a 47 mm filter holder containing the test fabrics. Total air flow through the DATS system is monitored by an orifice meter, while separate exhaust and supply blowers, along with a purge line, provide means for running as a closed loop system or exhausting up to 100% of the flow. By partially exhausting the system flow, the static pressure in the test chamber can be maintained at zero static pressure, thus preventing leaks into or out of the test chamber. For experiments done at 90% relative humidity, the purge line provided a means to introduce steam. Upstream of the test chamber, a port is located to introduce a test aerosol, generated from mineral oil in a DeVilbiss #40 nebulizer operated at 4 psig.

A 90° sampling probe and a Particle Measuring System (PMS) laser particle counting and sizing device allowed the aerosol concentration to be monitored in the test chamber section. To determine aerosol penetration through the fabrics, a downstream sample was taken from the air stream flowing through the fabric filter holder and compared with the upstream sample. Penetration is the ratio of the downstream concentration to the upstream. Air flow through the test fabrics was set at face velocities of 1.5, 5.0, and 15.0 cm/s using a calibrated rotameter. A Wang 2200 computer system facilitated data storage and performed the computations for determining aerosol size distributions and fractional penetrations from the PMS particle counting and sizing data.

Design of Experiments

Six materials were selected to be tested at three filtering face velocities under normal relative humidities (RH) present in the laboratory, which were found to vary from 20 to 35% RH, and at high

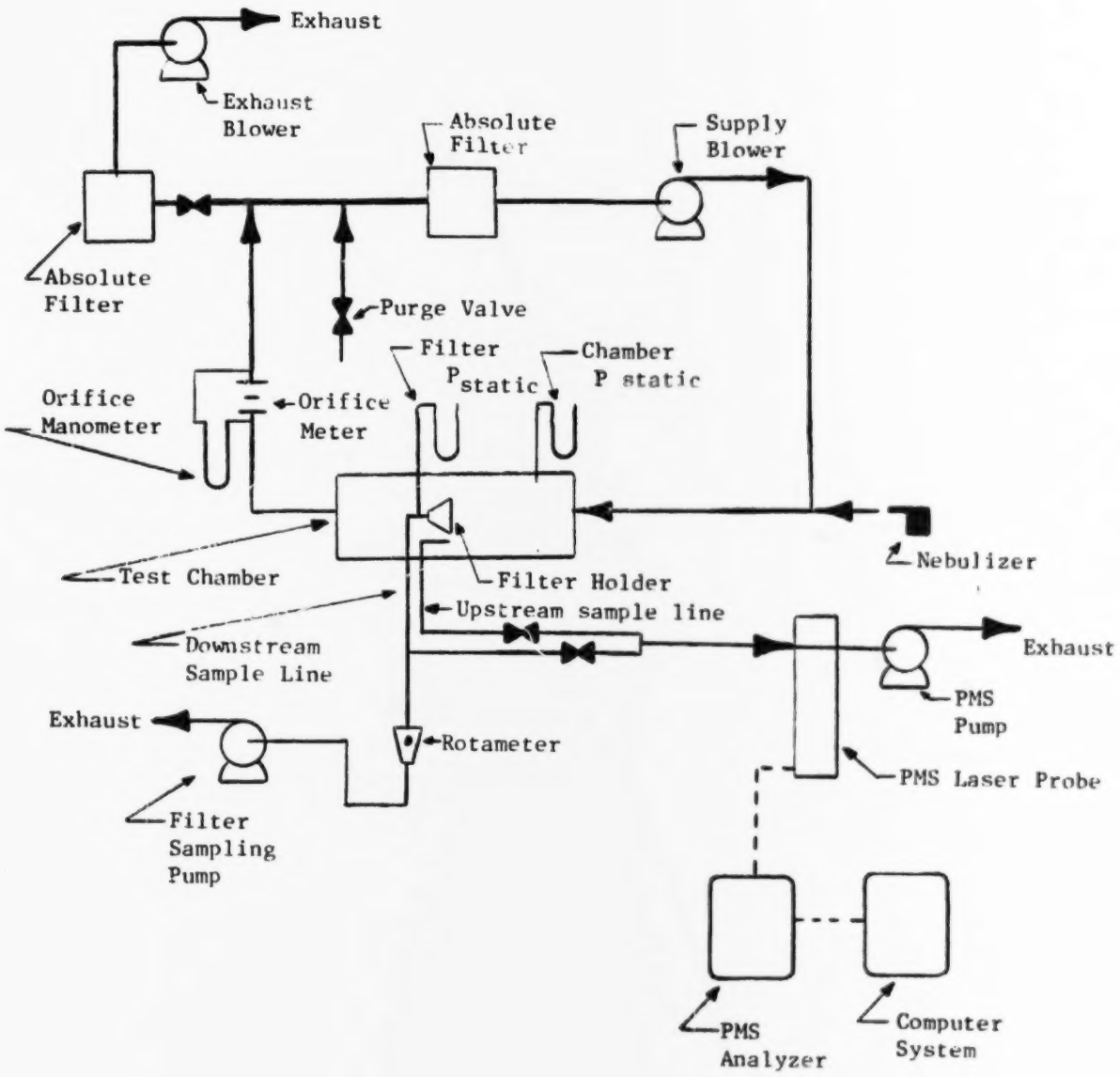

Figure 2.1. Dynamic aerosol test system (DATS) for expedient respirator study.

relative humidities (>90%). Table 2.1 lists each material, along with manufacturers' codes as found on the labels. For the high relative humidity conditions the NIOSH respirator was not tested nor was the low-quality towel. Because the low-quality towel (terry cloth) was a poor filter medium under normal conditions, it was abandoned in favor of the higher-quality wash cloth material (also referred to as "higher-quality towel") for further testing. Each of the four materials tested at high RH were allowed to soak in distilled water for ten minutes and then wrung dry by hand to remove excess water before being placed into the test filter holder.

For the low-RH experiments, each material was cut into 47 mm diameter circles to fit inside the filter holder and enough layers were placed to give a resistance of as close to 0.40 inch of water (0.40 in. H_2O = 1.0 cm H_2O = 100 Pa) as possible. The NIOSH respirator was tested using only one layer and the lower-quality towel and wash cloth thicknesses prevented layering more than two layers in the filter holder.

Flow through the DATS was set at 160 cfm to provide adequate dilution of the aerosol generated. The flow through the test filter was set at one of the three operating flow rates and a pressure drop reading was recorded. An upstream aerosol sample was taken by the PMS and the data recorded on the Wang 2200 system. Then an aerosol sample was taken from the downstream flow line of the filter holder to determine aerosol penetration through the filter material. This procedure was done twice for each filter material at the three filtering velocities. The PMS data from the duplicate penetration tests were combined to give fractional penetration by particle size. Several preliminary penetration tests were done at a given condition to assure upstream aerosol concentration was not changing during the test period and to give an indication of the statistical variation in the penetration measurements.

For the high humidity conditions the DATS system air was raised to 90% RH or higher by injecting steam. After equilibrium was reached, testing of each material was done as had been for the dry conditions.

Results

Tables 2.2 through 2.7 show the measured penetrations for the six materials for eight particle sizes and three face velocities. Penetration is the ratio of the downstream concentration to the upstream concentration, and the particle size is measured by light scattering. These results are presented graphically in Figures 2.2 to 2.7. (The face velocities are indicated by A, B, and C on the graph or by a number if more than 2 results were approximately the same.) The trends can be summarized as follows:

1. Penetration tends to decrease as particle aerodynamic diameter increases, for particles larger than 0.5 μm.

2. For particles larger than 1 μm in diameter, the penetrations generally were least at 15 cm/s and somewhat less at 5 cm/s than at 1.5 cm/s.

TABLE 2.1. MATERIALS TESTED FOR THIS REPORT

Material	Composition	Thread Count[b]	Manuf. Code
Broadway Terryweave (Low-quality towel)	90% cotton, 10% polyester		RN#50932 Method 2[a] col = 601
White Broadcloth (Handkerchief)	100% cotton	57/in x 64/in ($121/in^2$)	RN#16810
Blue Shirt	40% fortrel polyester, 60% cotton	46/in x 45/in ($91/in^2$)	20005 71 3
Springmaid Natural Charm (Nude color bed sheet)	100% cotton	87/in x 74/in ($161/in^2$)	50030 3
Wash Cloth - Terryweave (High-quality toweling)	88% cotton, 12% polyester dacron		Lady Pepperell Grandeur (Westpoint Perrell, Inc.)
3M Brand Dust Respirator			# 8710

a. Taken from manufacturer's markings.
b. Determined by us.

TABLE 2.2. MEASURED PENETRATION: NIOSH-APPROVED RESPIRATOR

particle diameter	Velocity 1.5 cm/s	5.0 cm/s	15 cm/s
.40700	.171000	.268000	.325000
.58100	.144000	.216000	.239000
.88400	.064000	.103000	.101000
1.40000	.028000	.043000	.030000
1.93000	.011000	.010000	.000000
2.30000	.000000	.000000	.000000
3.23000	.002000	.006000	.005000
4.75000	.000000	.000000	.000000

TABLE 2.3. MEASURED PENETRATION: COTTON SHEET

particle diameter	Velocity 1.5 cm/s	5.0 cm/s	15 cm/s
.40700	.780000	.778000	.788000
.58100	.839000	.858000	.823000
.88400	.761000	.656000	.615000
1.40000	.759000	.610000	.521000
1.93000	.482000	.341000	.122000
2.30000	.560000	.192000	.061000
3.23000	.253000	.190000	.019000
4.75000	.095000	.000000	.000000

TABLE 2.4. MEASURED PENETRATION: COTTON SHIRT

particle diameter	Velocity 1.5 cm/s	5.0 cm/s	15 cm/s
.40700	.782000	.787000	.824000
.58100	.866000	.851000	.899000
.88400	.747000	.717000	.543000
1.40000	.672000	.711000	.406000
1.93000	.425000	.471000	.051000
2.30000	.462000	.372000	.010000
3.23000	.456000	.281000	.008000
4.75000	.236000	.039000	.000000

TABLE 2.5. MEASURED PENETRATION: LOWER-QUALITY COTTON TOWEL

particle diameter	Velocity 1.5 cm/s	5.0 cm/s	15 cm/s
.40700	.883000	.916000	.929000
.58100	.998000	.972000	.999000
.88400	.835000	.882000	.840000
1.40000	.783000	.790000	.807000
1.93000	.944000	.663000	.384000
2.30000	.967000	.637000	.357000
3.23000	.811000	.554000	.262000
4.75000	.433000	.260000	.000000

TABLE 2.6. MEASURED PENETRATION: HIGHER-QUALITY COTTON TOWEL ("TOWEL.2")

particle diameter	Velocity 1.5 cm/s	5.0 cm/s	15 cm/s
.40700	.609000	.725000	.818000
.58100	.598000	.751000	.802000
.88400	.491000	.609000	.561000
1.40000	.410000	.516000	.451000
1.93000	.208000	.219000	.093000
2.30000	.203000	.248000	.055000
3.23000	.203000	.189000	.042000
4.75000	.049000	.000000	.025000

TABLE 2.7. MEASURED PENETRATION: COTTON HANDKERCHIEF

particle diameter	Velocity 1.5 cm/s	5.0 cm/s	15 cm/s
.40700	.698000	.793000	.810000
.58100	.742000	.830000	.777000
.88400	.647000	.663000	.489000
1.40000	.560000	.565000	.337000
1.93000	.468000	.184000	.023000
2.30000	.248000	.150000	.004000
3.23000	.240000	.111000	.014000
4.75000	.089000	.013000	.000000

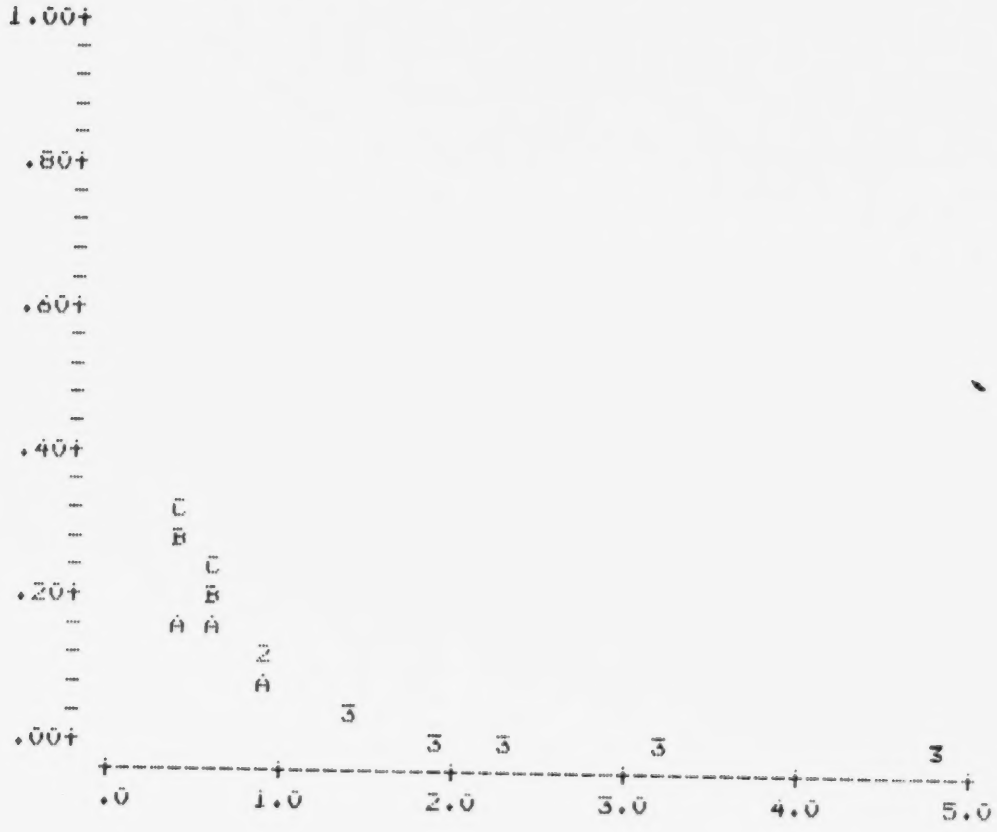

Figure 2.2. Measured penetration versus particle diameter (μm) for NIOSH-approved respirator. (A = 1.5 cm/s; B = 5 cm/s; C = 15 cm/s.)

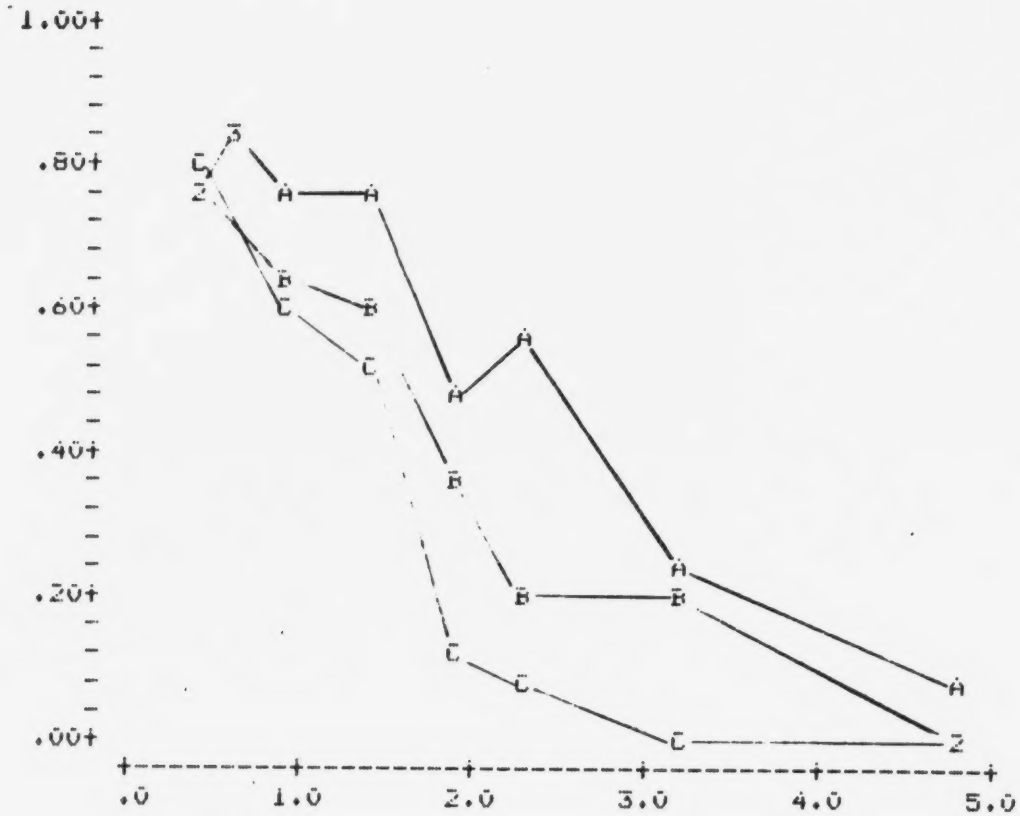

Figure 2.3. Measured penetration versus particle diameter (μm) for cotton sheet (12 layers). (A = 1.5 cm/s; B = 5 cm/s; C = 15 cm/s.)

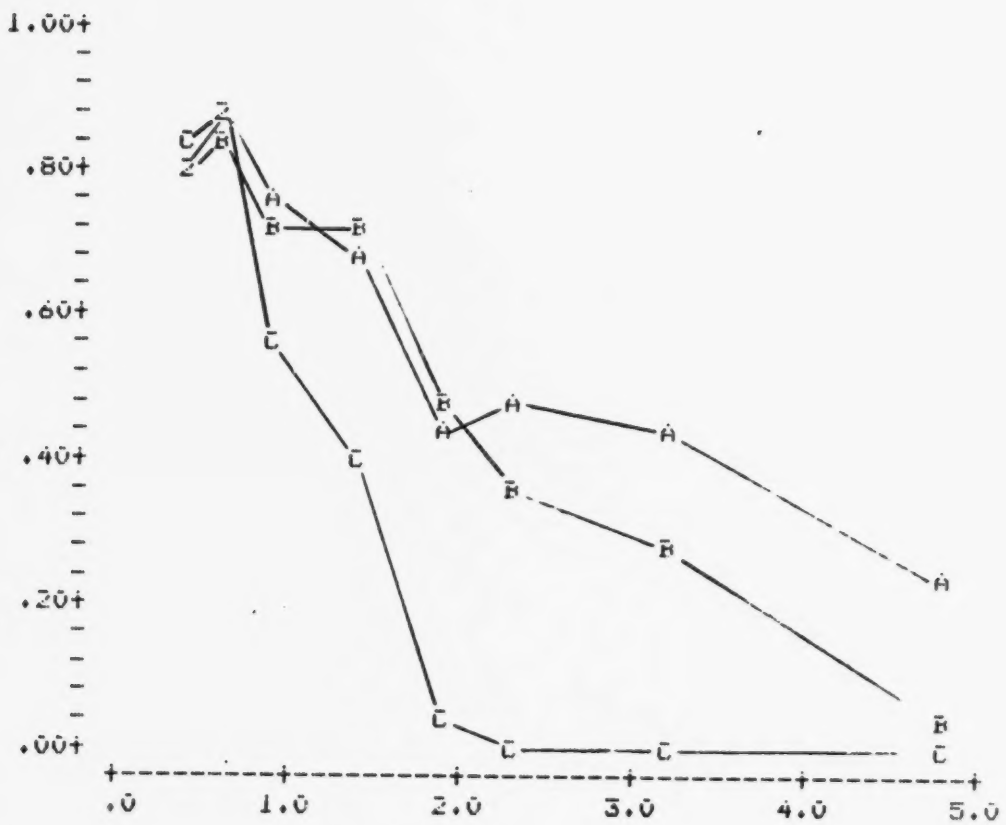

Figure 2.4. Measured penetration versus particle diameter (μm) for cotton shirt (8 layers). (A = 1.5 cm/s; B = 5 cm/s; C = 15 cm/s.)

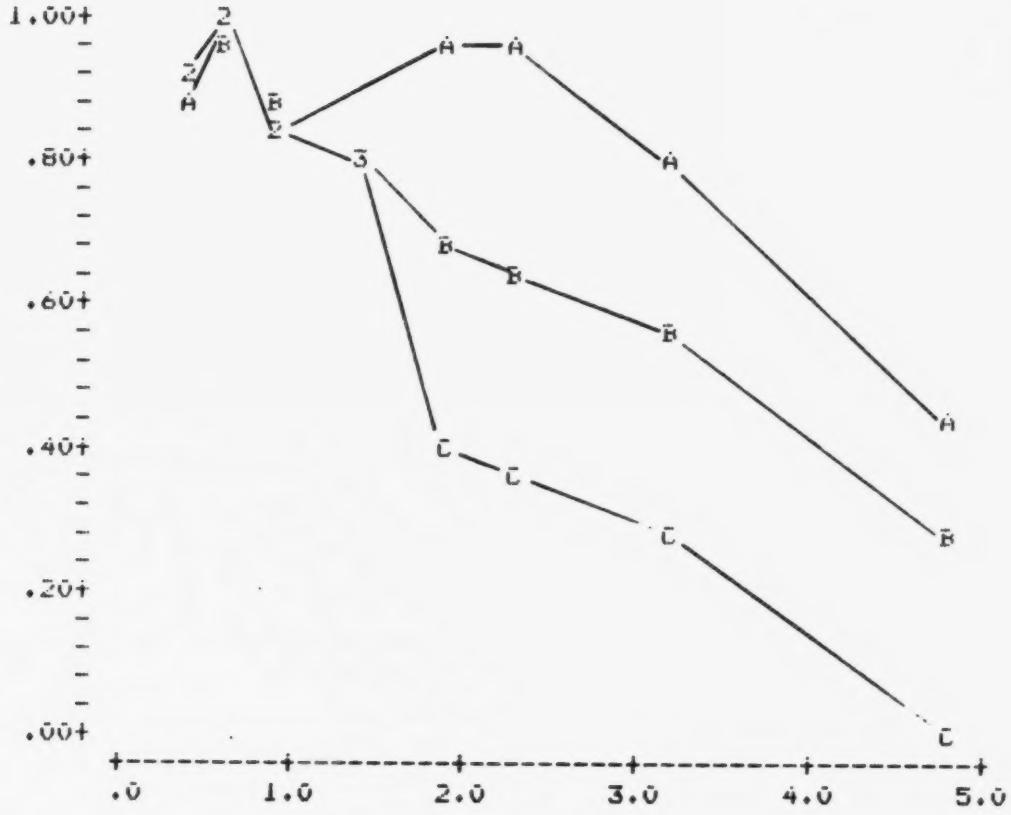

Figure 2.5. Measured penetration versus particle diameter (μm) for lower-quality cotton towel (4 layers). (A = 1.5 cm/s; B = 5 cm/s; C = 15 cm/s.)

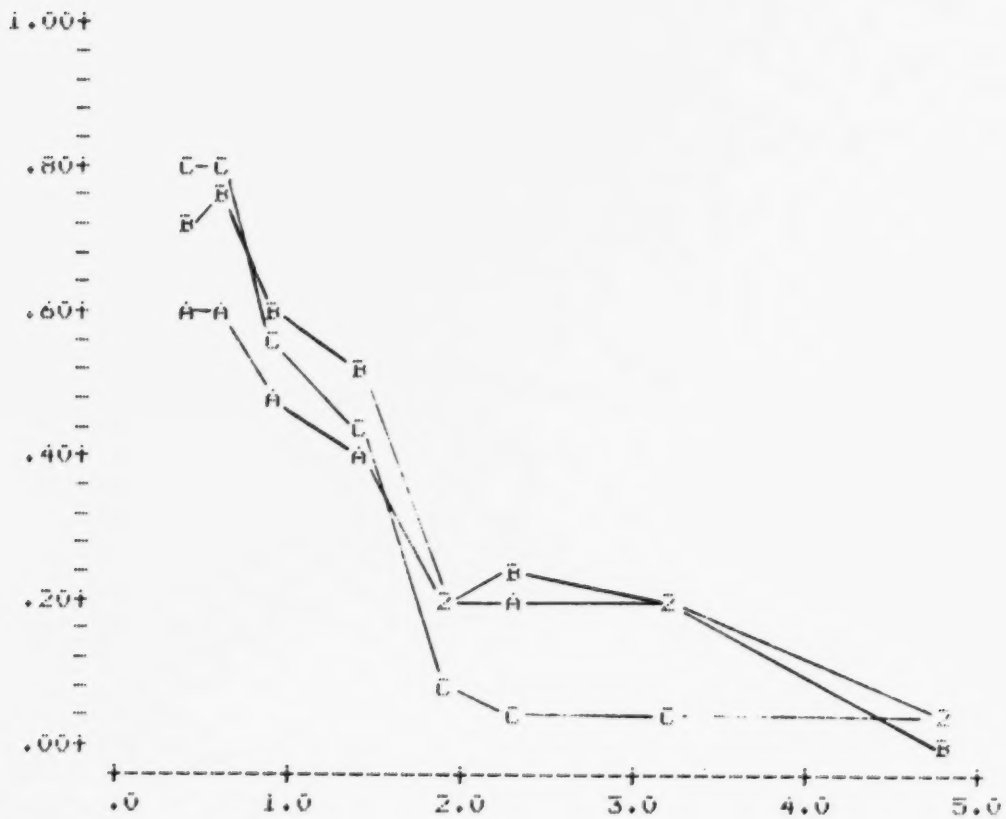

Figure 2.6. Measured penetration versus particle diameter (μm) for higher-quality cotton towel (2 layers). (A = 1.5 cm/s; B = 5 cm/s; C = 15 cm/s.)

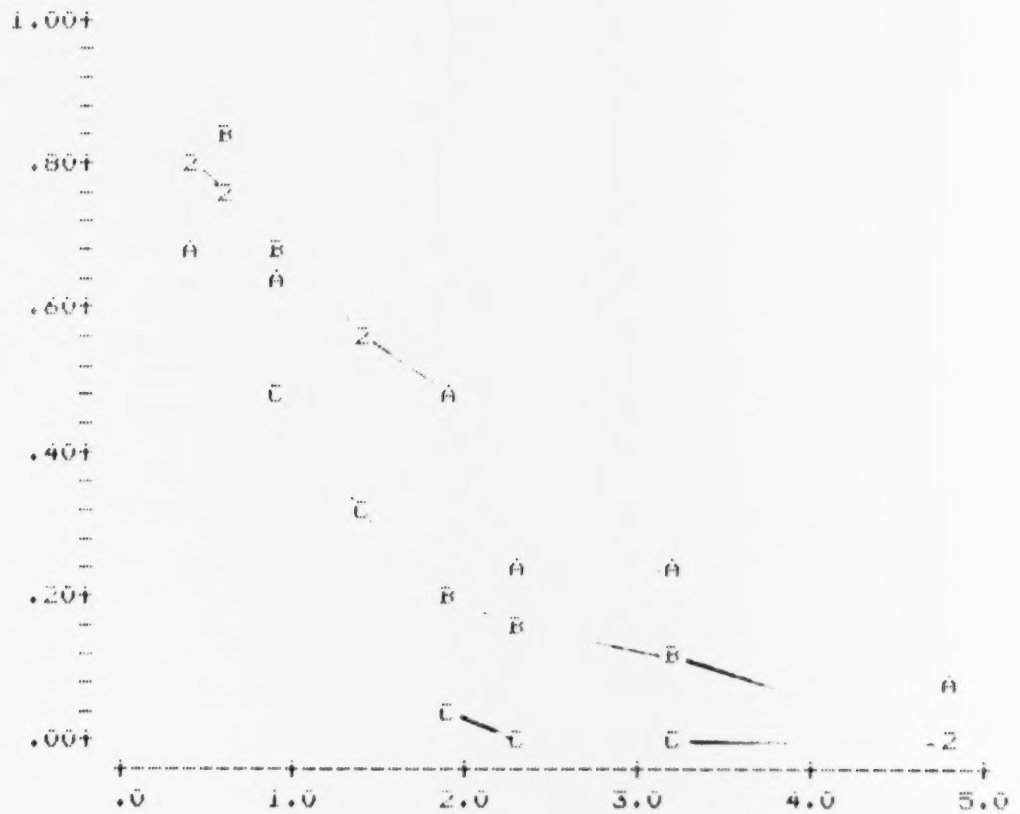

Figure 2.7. Measured penetration versus particle diameter (μm) for cotton handkerchief (10 layers). (A = 1.5 cm/s; B = 5 cm/s; C = 15 cm/s).

Figure 2.8 shows penetration versus particle diameter for the six materials. For the materials used (which resulted in somewhat different pressure drops), the respirator mask was markedly superior to the others. The lower-quality towel was least effective. The pressure drops (in Pa) measured for the dry fabrics are listed below; the numbers in parentheses are the number of layers:

Velocity (cm/s)	Respirator(1)	Sheet (12)	Shirt (8)	Lower-Quality Towel(4)	Higher-Quality Towel(2)	Handkerchief (10)
1.5	25	30	27	10	17	35
5.0	80	100	90	32	60	122
15.0	237	304	291	107	189	391

Figure 2.9 displays measured pressure drop versus face velocity. Figure 2.9 shows that, although some effort was expended in trying to match pressure drops, there were substantial differences in flow resistance for the various materials...for example, the lower-quality towel had only half the pressure drop of the respirator mask.

In order to compare the materials more generally, we calculated "quality factors" (q) by taking the negative logarithm of the penetration and dividing it by the pressure drop (ΔP)(Fuchs, 1964),

$$q = -\ln(c/c_0)/\Delta P \qquad (2.1)$$

in which c and c_0 are the downstream and upstream concentrations. The rationale for this is as follows: the penetration for n layers of the same material would decrease as $(c/c_0)^n$ while the pressure drop would increase as n times the pressure drop of one layer, so that the quality factor can be used to extrapolate to any thickness (any pressure drop). It depends on the material, the particle size, and the face velocity, but not on the thickness. Figure 2.10 shows the (measured) quality factors at 5 cm/s. (The logarithm of zero is ill-defined, so four observations were excluded.) These quality factors can be used to predict the penetration of the materials at any chosen pressure drop for the particle size and the velocity tested. The higher the quality factor, the less penetration at a given pressure drop, equivalently, the less pressure drop for a given penetration. Clearly, the respirator mask performed best. Of the other materials, the higher-quality towel (E = qtowel.2) and the bed sheet (B = qsheet) performed best, somewhat better than the lower-quality towel, the shirt, or the handkerchief.

The final table, Table 2.8, summarizes the quality factors for all the materials, particle sizes, and velocities tested dry. To aid in interpreting these numbers, we note that for a pressure drop of 1.0 cm H_2O = 10 mm H_2O (100 N/m^2 or Pa), the following quality factors will give the indicated penetrations:

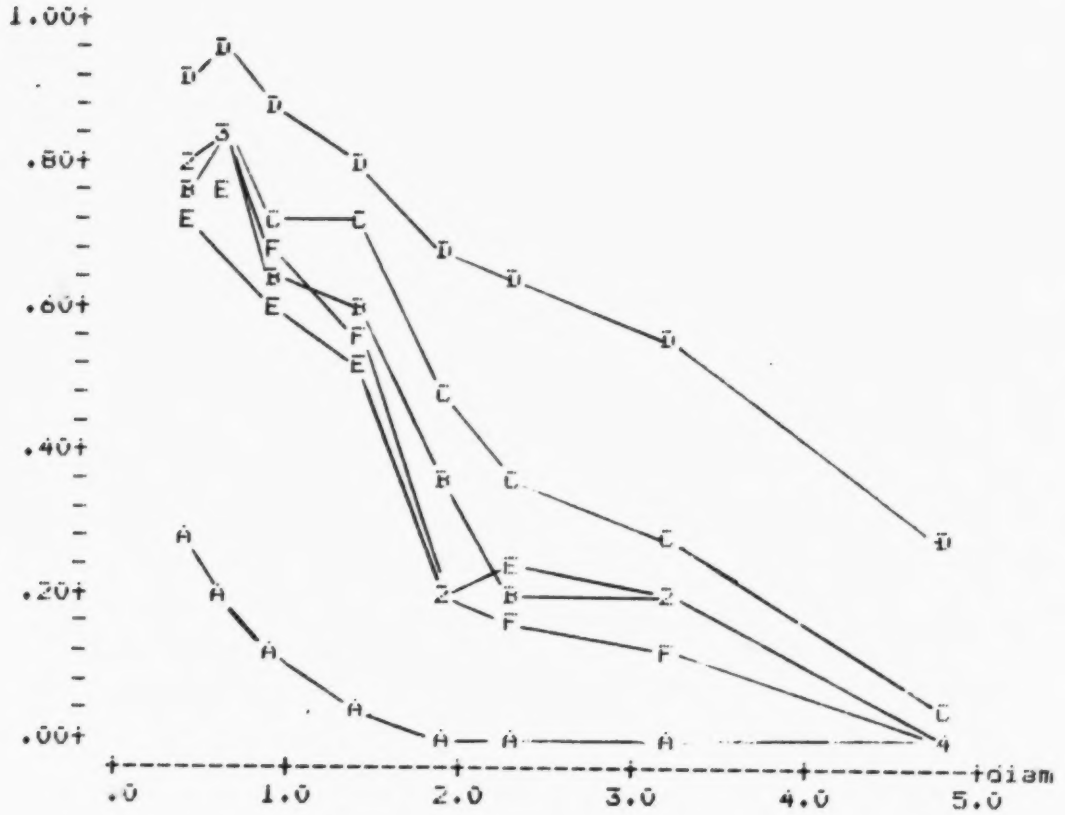

Figure 2.8. Measured penetration at 5 cm/s versus particle diameter (μm). (A = respirator; B = sheet; C = shirt; D = lower-quality towel; E = higher-quality towel; F = handkerchief.)

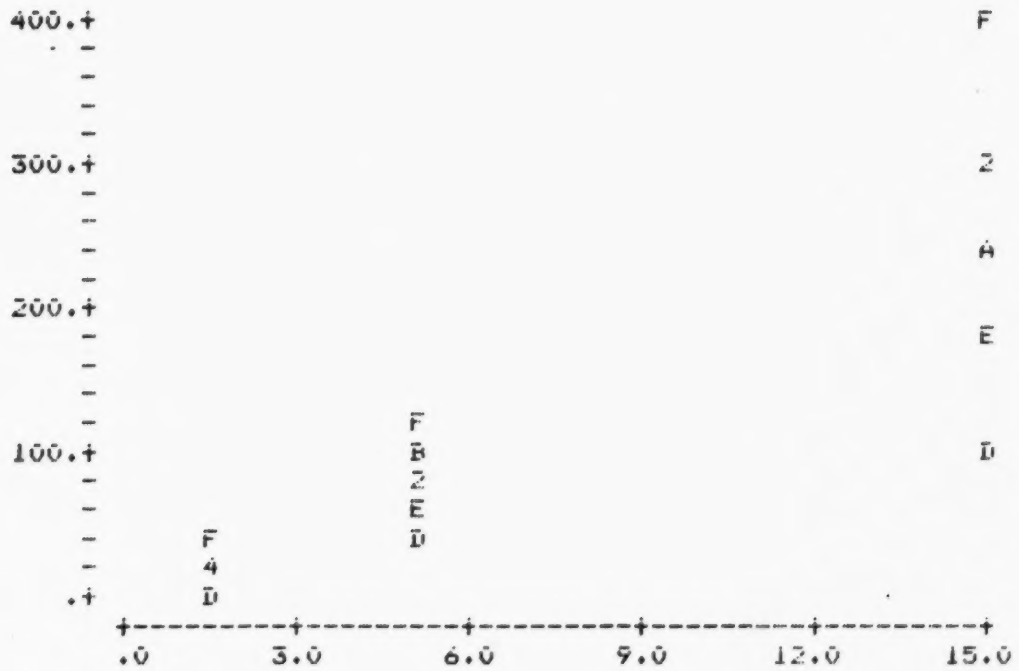

Figure 2.9. Measured pressure drops (Pa) versus velocity (cm/s). (A = respirator; B = sheet; C = shirt; D = lower-quality towel; E = higher-quality towel; F = handkerchief.)

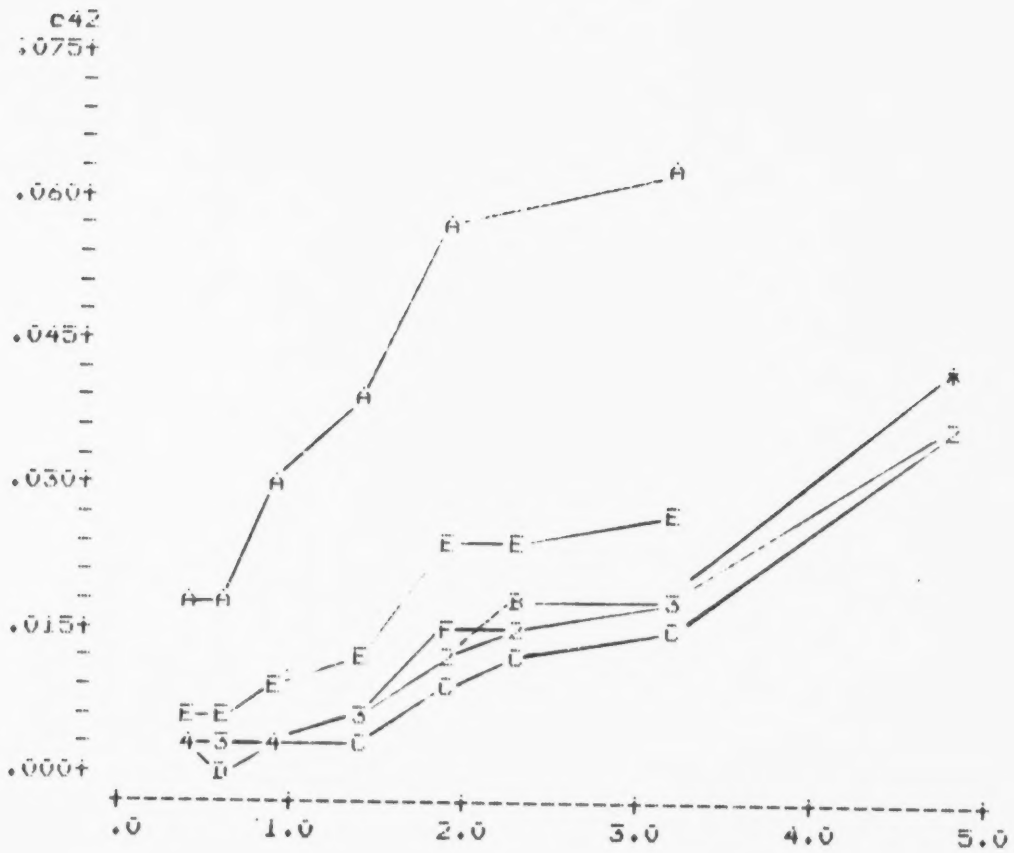

Figure 2.10. Quality factors (at 5 cm/s) versus particle diameter (μm). (A = qresp; B = qsheet, C = qshirt; D = qtowel; E = qtowel.2; F = qhandkchf.)

TABLE 2.8. MEASURED QUALITY FACTORS(DRY): ALL VELOCITIES

particle diameter (μm)	respirator	sheet	shirt	lower-quality towel	higher-quality towel	handkerchief
			1.5 cm/s			
.40700	.0709?7	.0083097	.0089745	.0124930	.028453	.0103137
.58100	.077829	.0058711	.0052507	.0002010	.029499	.0085601
.88400	.110396	.0091345	.0106456	.0181048	.040810	.0124902
1.40000	.143596	.0092225	.0148072	.0245605	.051153	.0166328
1.93000	.181119	.0244084	.0312287	.0057861	.090087	.0217810
2.30000	*******	.0193919	.0281821	.0033692	.091483	.0399?7?
3.23000	.249583	.0459654	.0286592	.0210329	.091483	.0409385
4.75000	********	.0787250	.0526979	.0840379	.173031	.0693953
			5 cm/s			
.40700	.0165257	.0025204	.0026721	.0027105	.0053813	.0019009
.58100	.0192329	.0015377	.0017999	.0008773	.0047917	.0015272
.88400	.0285269	.0042329	.0037113	.0038790	.0082988	.0033684
1.40000	.0394899	.0049628	.0038050	.0072821	.0110718	.0046794
1.93000	.0577958	.0108019	.0083991	.0126963	.0254130	.0138744
2.30000	*********	.0165689	.0110313	.0139322	.0253321	.0157489
3.23000	.0642068	.0166740	.0141611	.0182450	.0278783	.0180168
4.75000	*********	********	.0361914	.0416149	********	.0355?39
			15 cm/s			
.40700	.0047513	.0007843	.0006645	.0006878	.0010616	.0005390
.58100	.0060507	.0006412	.0003653	.0000093	.0011660	.0006434
.88400	.0096920	.0016002	.0020961	.0016284	.0030545	.0018500
1.40000	.0148237	.0021462	.0030941	.0020027	.0042078	.0027823
1.93000	*********	.0069247	.0102150	.0089391	.0125510	.0076493
2.30000	*********	.0092063	.0158074	.0096201	.0153267	.0141?39
3.23000	.0223983	.0130458	.0165734	.0125097	.0167517	.0109193
4.75000	*********	********	********	********	.0194931	*******

quality factor:	.007	.023	.046
penetration:	1/2	1/10	1/100

Under many of the conditions of particle size and face velocity and for many of the fabrics, reductions greater than a factor of two can be expected, if leakage around the materials can be kept relatively small.

Experimental Set-Up: Wet Materials

The test system was modified to allow the humidification of the air. For the "wet" tests, relative humidity in the test section was adjusted to be between 90 to 95% RH, partly to help keep the fabrics moist and partly to simulate exhalation. Each wetted material was allowed to reach a quasi-equilibrium state: with no aerosol being generated upstream, the air downstream was sampled with the particle measuring system (PMS) to be sure that droplets were no longer being emitted from the fabric. Testing for aerosol penetration was then done, as in the previous "dry" experiments. The lower-quality towel was dropped from further testing, and the NIOSH-approved respirator was not suited to operation while wet.

The data for the wet tests are listed in Table 2.9. with particle diameter followed by the measured penetrations for the sheet, the shirt, the towel ("twl.2") and the handkerchief ("hank"); the additional letters l for the low-velocity tests (1.5 cm/s) and h for the high-velocity tests (15 cm/s) distinguish them further from the 5 cm/s tests. The effectiveness of the towel on particles with diameters larger than 1 μm is particularly striking. Penetration is least at the highest velocity in almost all cases, showing impaction is a major particle collection mechanism. The data for the four materials at 1.5 cm/s are plotted in Figure 2.11. (A represents the sheet, B the shirt, C the towel, and D the handkerchief). The superiority, in terms of penetration, of the high-quality towel (points labeled C) is evident.

The pressure drops measured for these materials were (Pa):

	sheet(12)	shirt(8)	towel(2)	handkerchief(10)
1.5 cm/s	95	62 - 75	22	162 - 374
5 cm/s	347	249	92	896 - 1494
15 cm/s	1021 - 4233	872 - 3237	344 - 266	2689

The number of layers is shown in parentheses. Paired numbers indicate

TABLE 2.9. PENETRATIONS (WET)

particle diameter (μm)	sheet	shirt	higher-quality towel	handkerchief
		1.5 cm/s		
.40700	.831000	.999000	.483000	.937000
.58100	.932000	.939000	.287000	.980000
.88400	.791000	.434000	.078000	.842000
1.40000	.782000	.213000	.039000	.869000
1.93000	.539000	.061000	.000000	.495000
2.30000	.285000	.027000	.000000	.350000
3.23000	.428000	.007000	.000000	.307000
4.75000	.055000	.000000	.000000	.041000
6.25000	.000000	.000000	.000000	.000000
		5 cm/s		
.40700	.847000	.798000	.447000	.921000
.58100	.799000	.646000	.188000	.999000
.88400	.460000	.282000	.055000	.533000
1.40000	.301000	.144000	.022000	.245000
1.93000	.016000	.000000	.015000	.016000
2.30000	.005000	.000000	.000000	.000000
3.23000	.005000	.000000	.009000	.000000
4.75000	.000000	.000000	.082000	.000000
6.25000	.000000	.000000	.000000	.000000
		15 cm/s		
.40700	.905000	.811000	.289000	.612000
.58100	.843000	.565000	.095000	.265000
.88400	.330000	.162000	.021000	.041000
1.40000	.091000	.033000	.004000	.002000
1.93000	.000000	.000000	.000000	.000000
2.30000	.000000	.000000	.005000	.000000
3.23000	.000000	.000000	.000000	.000000
4.75000	.000000	.000000	.000000	.000000
6.25000	.000000	.000000	.000000	.000000

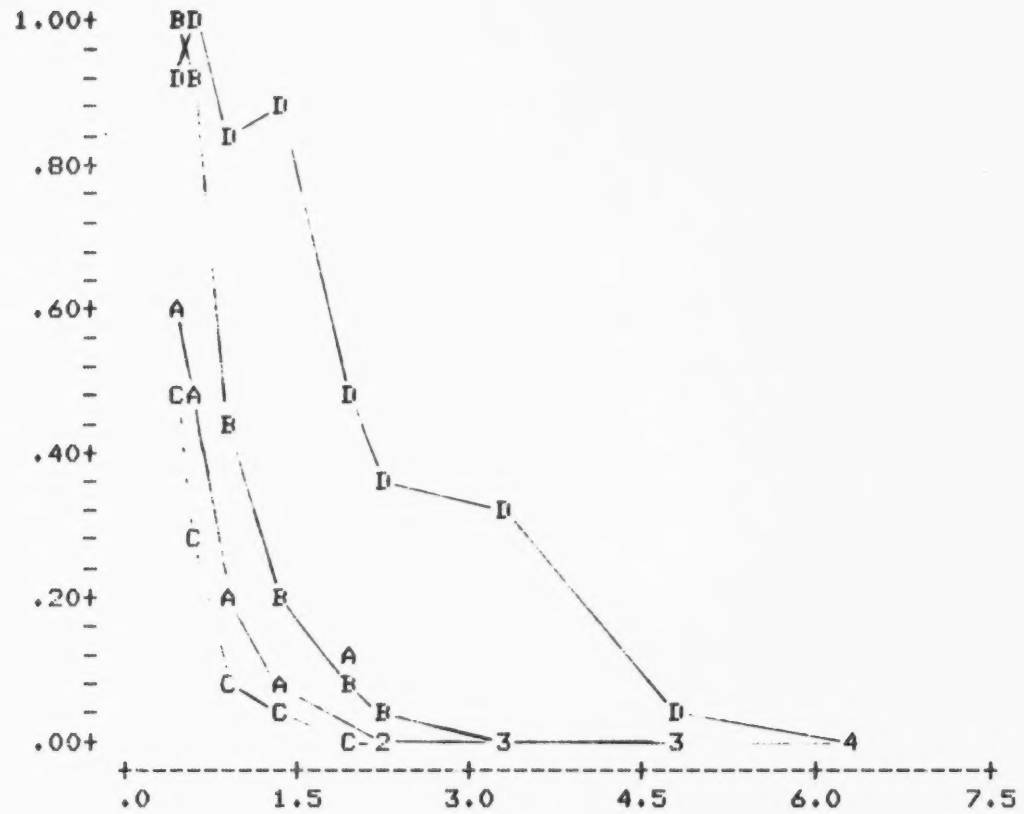

Figure 2.11. Measured penetration (wet) at 1.5 cm/s versus particle diameter (μm). (A = sheet; B = shirt; C = higher-quality towel; D = handkerchief.)

that the material's resistance changed during the period of the test; the lower number is the pressure drop after one-half hour; the higher number is the initial pressure drop. (The pressure drop for the handkerchief was initially beyond the capacity of the manometer, 23 in. H_2O.)

Pressure drops greater than 100 Pa are uncomfortable (Guyton et al., 1959), so operation near 1.5 cm/s would be preferred. Figure 2.11 shows penetration versus particle diameter for 1.5 cm/s face velocity. The penetrations (Pn*) and pressure drops (ΔP) (the half-hour values) were used to calculate the quality factors

$$q = -\ln(Pn^*)/\Delta P \qquad (2.2)$$

given in Table 2.10. This table follows the same format as the preceding table. (The asterisks come from evaluating the logarithm of zero.) Quality factors greater than 0.023 mean that at a pressure drop of 100 Pa (1 cm of water), the concentration would be reduced by a factor of ten. The wet towel and the wet shirt performed this well for particles larger than 1 μm at the intermediate-velocity conditions. In general, the wetted towel and shirt did better than the dry and the reverse was true for the sheet and handkerchief.

Data Analysis: Reproducibility of Penetration Measurements

Typically, penetration was determined by taking an upstream count and a downstream count, then forming the ratio; this would be repeated a second time. The penetrations reported were then the averages of two such downstream-to-upstream ratios. To estimate the reproducibility of these penetration averages, the procedure was repeated three times for the bed sheet at 5 cm/s (for results roughly typical of the entire experimental range). Table 2.11 shows the particle diameters, the original penetrations, the penetrations measured in the second, third, and fourth runs of the same material (each run shows the average of two count ratios). Also shown in the table are the means of the penetrations and the standard deviations (two-thirds of such determinations would be expected to fall within the range of the mean plus and minus one standard deviation). The standard deviations range from about two percent to about six percent for penetrations ranging from sixteen percent to eighty percent. The penetrations versus particle size are plotted in Figure 2.12. The standard deviations are one-fourth or less of the mean penetrations.

Comparisons of Dry Material Penetration with Guyton et al. Data

As we tried to compare our results with those of Guyton et al., it became clear that performing the comparison is more difficult than we originally thought. One approach might be to use the pressure drops given by these authors and the quality factors we measured and predict the performance of the fabrics, then compare our predictions with their measurements. Unfortunately, those pressure drops are for 10 lpm flowing through 12.5 cm^2 of material, whereas the pictures and descriptions given by Guyton

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TABLE 2.10. MEASURED QUALITY FACTORS (WET): ALL VELOCITIES

particle diameter (μm)	sheet	shirt	higher-quality towel	handkerchief
		1.5 cm/s		
.40700	.00.3565	.0000.81	.·32474	.000402.
.58100	.0007443	.00.0111	.055702	.0001248
.85400	.0024778	.0134090	.113835	.0010828
1.40000	.0025938	.0249426	.144765	.0008675
1.93000	.0065318	.0449298	*******	.0043447
2.30000	.0132664	.0586228	*******	.006480-
3.22000	.0088578	.0797084	*******	.0072982
4.75000	.0306534	********	********	.0187053
6.25000	*******	********	*******	********
		5 cm/s		
.40700	.0004761	.00030821	.0087305	.00009.8.
.58100	.0006437	.00.75424	.0181403	.00000112
.85400	.0022278	.00503070	.0314818	.00070.05
1.40000	.0034462	.00775290	.0414275	.0015890?
1.93000	.0118622·	*********	.0455846	.0048130?
2.30000	.0151988	*********	********	*********
3.22000	.0151838	*********	.0511292	*********
4.75000	*******	*********	.0271468	*********
6.25000	*******	*********	*******	*********
		15 cm/s		
.40700	.00008778	.00024038	.0046591	.00018250
.58100	.00018729	.00065511	.0088345	.00048284
.85400	.00108597	.00208854	.0145000	.00118773
1.40000	.00234783	.00391423	.0207239	.00231055
1.93000	*********	*********	********	*********
2.30000	*********	*********	.0198853	*********
3.22000	*********	*********	********	*********
4.75000	*********	*********	********	*********
6.25000	*********	*********	********	*********

TABLE 2.11. REPLICATE DETERMINATIONS OF PENETRATION FOR BED SHEET AT 5 CM/S

diameter	original	second	third	fourth	mean	standard deviation
.40700	.778000	.737000	.791000	.759000	.76625	.0235
.58100	.858000	.780000	.792000	.753000	.79575	.0446
.88400	.656000	.637000	.673000	.619000	.64625	.0234
1.40000	.610000	.624000	.579000	.578000	.59775	.0230
1.93000	.341000	.219000	.237000	.213000	.25250	.0599
2.30000	.192000	.165000	.251000	.139000	.18675	.0480
3.23000	.190000	.149000	.182000	.112000	.15825	.0356
4.75000	.000000	.000000	.013000	.010000	.00575	.00675

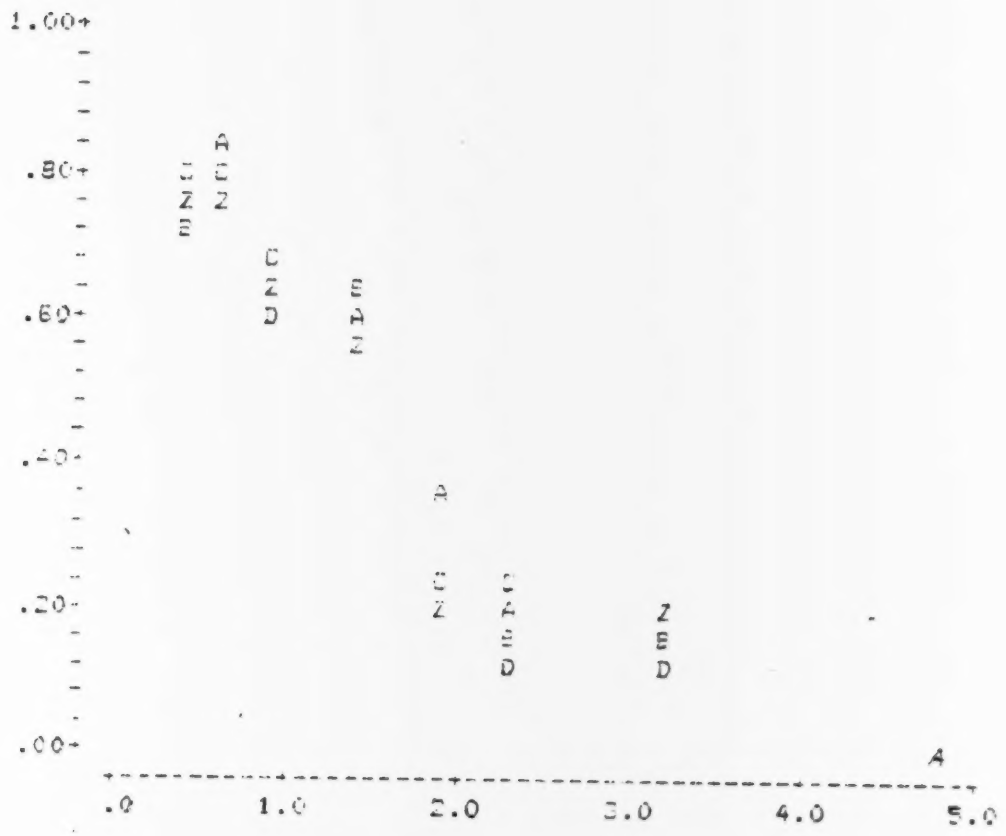

Figure 2.12. Replicate penetrations for bed sheet (12 layers) at 5 cm/s versus particle diameter (μm). (A to D = first to fourth runs.)

et al. suggest the area of fabric through which air passed when breathed by the volunteers was more like 50-100 cm^2, and there were no pressure drop readings taken during the tests with the volunteers. This ruled out the quality factor approach. The next best method seemed to be to accept 50-100 cm^2 as an estimate of the area and 10 lpm as an estimate of the breathing rate, giving a face velocity of 10^4 $cm^3/(50\text{-}100\ cm^2)(60\ s)$ or about 1 to 3 cm/s. The next step was to use the measured penetration characteristics for our fabrics at 1.5 cm/s and calculate the penetration expected for an aerosol of the size distribution Guyton et al. reported, having a number median diameter of 1.28 μm and a geometric standard deviation of 1.5.

Two methods were used to predict the penetration of our fabrics for an aerosol of d_{50} = 1.28 μm and σ_g = 1.5: First, the aerosol log normal number size distribution times the penetration was integrated over the particle size range. This was the "polydisperse" penetration estimate. Since the aerosol sizing technique (cascade impactor) tends to give an apparent broadening of the particle size distribution, we also calculated a "monodisperse" penetration, simply the penetration for the particle size we measured that was closest to the number median (namely, 1.40 μm). This was the "monodisperse" penetration estimate. These penetrations, "pn.poly" and "pn.mono", are given in Table 2.12 for each of the eight fabric/thickness combinations that correspond most closely to the Guyton et al. conditions. The first column contains an identifying number; the second gives the pressure drop (mm H_2O) measured by Guyton et al. and the third column gives the penetration they measured. (The final column is the pressure drop in Pa.) In each case the penetration calculated assuming the aerosol was monodisperse agreed well with the penetration calculated assuming the aerosol was polydisperse but neither agreed well with the data of Guyton et al., the calculated penetrations being higher consistently. If we had used the values we measured for 5 cm/s, the discrepancy would be somewhat greater, not less. This means that the fabrics tested on human volunteers by Guyton et al. performed better than we would have predicted, given the measured particle size distributuion and our measured penetration as a function of particle size for similar fabrics.

How can the differences be explained? Their active filtration area may have been somewhat larger than 100 cm^2, which would have improved the performance, but it is hard to imagine its being very much larger, and the breathing rate may not have been as low as 10 lpm, offsetting this. Our fabrics were somewhat different from theirs, but it is not likely that these differences would lead to consistently smaller penetration for the Guyton et al. set than for our own. The exhalation and humidification of the fabrics may have decreased penetration. It may be that the aerosol they used to determine penetration was not as fine as their cascade impactor measurements indicated, for the following reasons:

1. There is a tendency for some of the larger particles to rebound off one stage and get captured on the next.

2. The penetration was measured by Guyton et al. by analyzing the material

TABLE 2.12. PENETRATIONS AND PRESSURE DROPS OF GUYTON ET AL. FABRICS

fabric test number	pressure drop (mm H_2O)	measured penetration	calculated penetrations		pressure drop (Pa)
			pn. mono	pn. poly	
1.	36.	.058000	.395000	.388000	360.00
2.	13.	.086000	.000000	.000000	130.00
3.	18.	.111000	.628000	.607000	180.00
4.	11.	.149000	.410000	.390000	110.00
5.	5.	.261000	.640000	.613000	50.00
6.	22.	.280000	.977000	.963000	220.00
7.	3.	.298000	.000000	.000000	30.00
8.	7.	.345000	.905000	.887000	70.00
9.	84.	.370000	.000000	.000000	840.00
10.	98.	.374000	.000000	.000000	980.00
11.	180.	.437000	.000000	.000000	1800.00
12.	2.	.445000	.000000	.000000	20.00
13.	6.	.500000	.000000	.000000	60.00
14.	5.	.524000	.000000	.000000	50.00
15.	3.	.654000	.951000	.939000	30.00
16.	2.	.725000	.943000	.933000	20.00

captured by a second filter, held in the mouth, which did not capture all the smallest particles, underestimating penetration despite their correction factor.

3. Some other aspect of the bacterial particles, perhaps their shape, may have led them to be collected more efficiently than our test particles of the same aerodynamic diameter.

4. The aerosol size distribution may have been sufficiently different from a log normal with $\sigma_g = 1.5$ that the number median we calculated from their mass median (2.1 μm) is too small.

Had the penetrations through the Guyton et al. fabrics been, as we expected, greater than predicted from our tests, we would have calculated an estimated leakage as follows: The measured penetration (Pn*) would be the sum of the penetration through the fabric (Pn) and the leakage around the fabric. The leakage, the ratio of the leakage flow (Q") to the total flow (Q), can be shown to be

$$Q"/Q = (Pn* - Pn)/(1 - Pn). \qquad (2.3)$$

Our analysis showed Pn* < Pn, which makes Q"/Q negative, a physical impossibility.

TESTS WITH GAS AND VAPORS

Although Guyton et al. worked with aerosols only, their interest being protection from biological aerosols, our goal was to determine the potential efficacy of expedient methods of respiratory protection not only for aerosols which might be emitted during a major reactor accident, but also for gas and vapors expected to accompany such an event, Kr, I_2, CH_3I. It was expected that these would be collected much less readily than would particles larger than 1 μm in diameter, so less effort was budgeted for these tests. As will be seen, the effectiveness of the cloths on Kr and I_2 (wet cloth) was appreciable.

Noble Gas (Kr) Retention: Background

A noble gas such as Kr or Xe does not react, so that retaining it on a material involves only adsorption, in a dynamic equilibrium between the adsorbed layer and the gas. Radioactive Kr flowing to the fabric will be delayed in passing through while this dynamic equilibrium is established. The measurements described next indicate the amount of Kr associated with the cloth surface, which serves as a reservoir for this mixing and delaying process.

Noble Gas (Kr) Retention: Measurements

Air at 24-27°C temperature and one atmosphere pressure was used to dilute Kr. The mixture was passed through a cylindrical vessel packed with various cloths. A record of Kr concentration versus time (measured at the outlet of the flow, with an ionization chamber) was used to determine the amount of Kr retained per gram of the fabric materials. Table

2.13 shows the fabrics, the fabric density (as the weight in mg of a circular sheet 45 mm in diameter), the amount of fabric used, the volume of Kr retained in the fabric, and the retention coefficient (in cm^3 of Kr at NTP retained per g of fabric). It is noteworthy that these values are about one-third (or more) the retention values for charcoal, widely used to detain noble gases. At a concentration of 1 $\mu g/m^3$ Kr (2.7×10^{-4} cm^3/m^3 at NTP) in air, 1 cm^3 of Kr retained on the cloth is contained in a total volume of $4 \times 10^3 m^3$ of air, in comparison with the approximately 15 m^3 an adult normally inhales in 24 hours.

Kr Retention Measurements: Interpretation

In their extensive review of the theoretic and experimental literature on absorption of Kr and Xe by activated charcoal, Underhill and Moeller (1980) came to the following conclusions:

1. The 5th percentile and 95th percentile values for the adsorption coefficient, k (cm^3 at NTP per g of charcoal) at 25°C were 22 and 72.

2. The adsorption coefficient does not increase directly with surface area.

3. The adsorption coefficient does not change with carrier gas velocity.

4. The adsorption coefficient changes negligibly with concentration for Kr concentrations substantially smaller than 1 percent, and certainly in the ppm region and less.

In a personal communication, Underhill pointed out that the atmospheric concentrations of Kr (1.1 ppm) and Xe (0.09 ppm) are larger than the concentration additions expected (outside the plant boundary) in a core melt accident, so that the major mechanism will be isotopic dilution, with the previously-adsorbed noble gases serving as reservoirs of non-radioactive atoms to exchange with the influent radioactive atoms. Presumably, this kind of exchange is being seen in the tests for the adsorption coefficient of Kr conducted with radioactive Kr (at ppm concentrations) and ambient air.

From the foregoing, we conclude that our measurements of adsorption coefficients give a fairly accurate indication of the amount of radioactive Kr which would be detained by the cloths at the low levels ($<<$ 1 ppm) projected for hypothetical reactor accidents. The adsorption coefficients of xenon from air on charcoal are about an order of magnitude larger than those of Kr, and they may well have roughly the same ratio for cloth fabrics.

The isotopic dilution process can be described as follows: Assume a frame of reference which is moving with the gas, such as a parcel of gas. The adsorption process does not recognize any difference between the isotopes, having gas concentrations c_1 and c_2. Assume that the initial concentration of the radioactive species (species 2) is much smaller than that of the non-radioactive (ambient) isotopic species (species 1). As

TABLE 2.13. NOBLE GAS (Kr) RETENTION

	Weight per sheet of 45 mm diameter (mg)	Weight of fiber used (g)	Retention Volume (liters)	K (cc(NTP)/g)
high-quality towel (face cloth)	77.23	21.1	1.66	79
shirt	24.88	61.0	1.73	28
sheet	18.16	45.0	1.29	29
handkerchief	24.38	41.4	1.78	43
low-quality towel	49.07	26.0	1.90	73

the gas moves through the adsorber, the total concentration will remain almost unchanged:

$$Dc/Dt = Dc_1/Dt + Dc_2/Dt = 0 \qquad (2.4)$$

(D/Dt is a material derivative, moving with the gas). Assume that the rate of desorption from the surface is proportional to the amount on the surface (such as mass per unit area), m, and the adsorption rate is proportional to the concentration in the gas, then:

$$Dc_1/Dt = km_1 - k'c_1 \qquad (2.5)$$

$$Dc_2/Dt = km_2 - k'c_2 \qquad (2.6)$$

At equilibrium, not only is Dc/Dt = 0 but so are the derivatives of the isotopic species concentrations, which leads to

$$c_1/c_2 = m_1/m_2 \qquad (2.7)$$

The outlet concentration (if the absorbing material is thick enough for this equilibrium to be reached) will be in proportion to the relative amounts of the two isotopes on the surfaces, and their total concentration will be the same as the inlet. If the inlet concentrations are 1000 ppb and 10 ppb and the surface has 1000 times as much of 1 than of 2 (which is roughly the case when the adsorber has still captured only trace amounts of species 2), then the outlet concentrations will be 1009 ppb of species 1 and 1 ppb of species 2, a ten-fold dilutional reduction of species 2.

The kinetics of the situation, again following a parcel, are initially as follows:

$$Dc_1/Dt \doteq 0 \qquad (2.8)$$

$$Dc_2/Dt = -Dc_1/Dt = -k'c_2 \qquad (2.9)$$

and as the parcel moves through the adsorber the concentration of c_2 decreases as exp(-k't), with the concentration of c_1 increasing to keep $c_1 + c_2$ constant. (The variable t is really the distance into the bed divided by the mean gas velocity.)

Penetration of Fabrics by Methyl Iodide (CH_3I)

The ability of two of the fabrics, the higher-quality toweling and the bed sheet, to retain methyl iodide was tested by placing each of the fabrics in a filter holder, passing air containing methyl iodide through the fabrics, and measuring the methyl iodide upstream and downstream from the fabrics.

The basic set-up is shown in Figure 2.13. The Dynacalibrator TM maintained a diffusion tube containing methyl iodide at a constant temperature and subjected the vapor to a constant dilution. (Generation rate

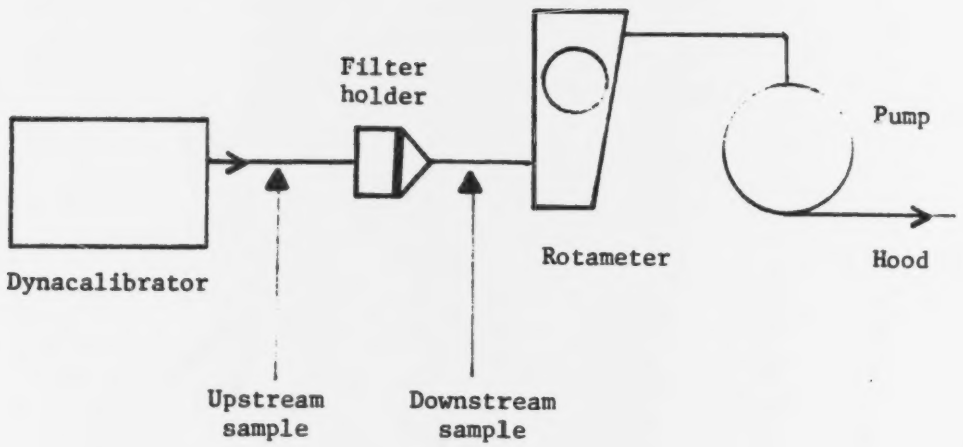

Figure 2.13. Set-up for CH_3I experiments.

was about 1.2×10^{-4} g/min.) Once the generator had reached equilibrium, one or more layers of cloth (one for the toweling, four for the bedsheet) were placed in the filter holder and 1.0 lpm of the mixture flowed through the fabrics. After 1, 3, 10, or 30 minutes an upstream or a downstream measurement was made.

The tests were designed to use the fabrics in conditions for which they would have no CH_3I, or negligible amounts, adsorbed on them before the tests occurred. Thus, the four-layer bed sheet test materials and the wet towel samples were changed after each test. The other materials were subjected to several minutes of clean air flow between runs. As will be seen, the materials all showed very little ability to pick up CH_3I.

The sample was 50 µL, taken with a syringe and brought immediately to the gas chromatograph, which had a flame ionization detector and an integrator. Two peaks were observed: the first was due to the air (oxygen), the second due to methyl iodide. The areas of both peaks were determined with the integrator, from which the ratio of methyl iodide to air in each sample could be obtained.

Table 2.14 shows the penetrations measured after 1, 3, 10, and 30 minutes, the mean penetration, the standard deviation of the four readings making up the mean, and the 95 percent confidence interval associated with the mean (95 percent of the time, one would expect, the true mean should fall within this range, if only random errors are occurring in the measurements). None of the fabrics caused a statistically significant decrease in concentration of methyl iodide.

Penetration of Fabrics by Iodine (I_2) Vapor

Although methyl iodide penetrated the wet and dry fabrics readily, it will be shown below that wetted fabrics produced reductions in iodine concentration that were statistically significant and could have practical significance, as well. These tests were, as with CH_3I, carried out with the higher-quality towel and the sheet.

I_2/Sheet Test Methods

The experimental set-up for the tests with I_2 vapor is shown in Figure 2.14. Air was drawn through a dessicant to a tee, allowing it to be divided between a direct path to the two filter holders and a path which passed through a U-tube filled with iodine crystals. The flow through the iodine crystals was controlled with a pinch clamp valve and monitored with a rotameter. The mixture, or just dry air, was split between the two filter holders and then flowed to bubblers and rotameters. When iodine was introduced, the system was allowed to run with air for a minute or two, then given five minutes of air/I_2 mixture, then another minute or two of air only, to make sure that the I_2 that had been introduced was carried through the system. Thus, the two filter holders should have experienced the same iodine vapor concentrations. (The filter holders were identical, 47 mm in diameter.)

TABLE 2.14. CH_3I/FABRIC RESULTS

Fabric	Penetration (1, 3, 10, 30 min) Measured	Mean	Std. Dev.	95% C.I.
sheet-dry[a]	1.17 .76 .94 .73	.90	.20	(.58, 1.22)
sheet-water[a]	1.09 .75 .82 .82	.87	.15	(.63, 1.11)
sheet-$NaHCO_3$[a]	1.17 .92 .91 .98	.99	.12	(.80, 1.18)
towel-dry[b]	.88 .99 .82 1.02	.93	.09	(.78, 1.08)
towel-water[b]	1.11 .98 1.02 .89	1.00	.09	(.86, 1.14)

a. Four layers at 1.0 cm/s
b. One layer at 1.0 cm/s

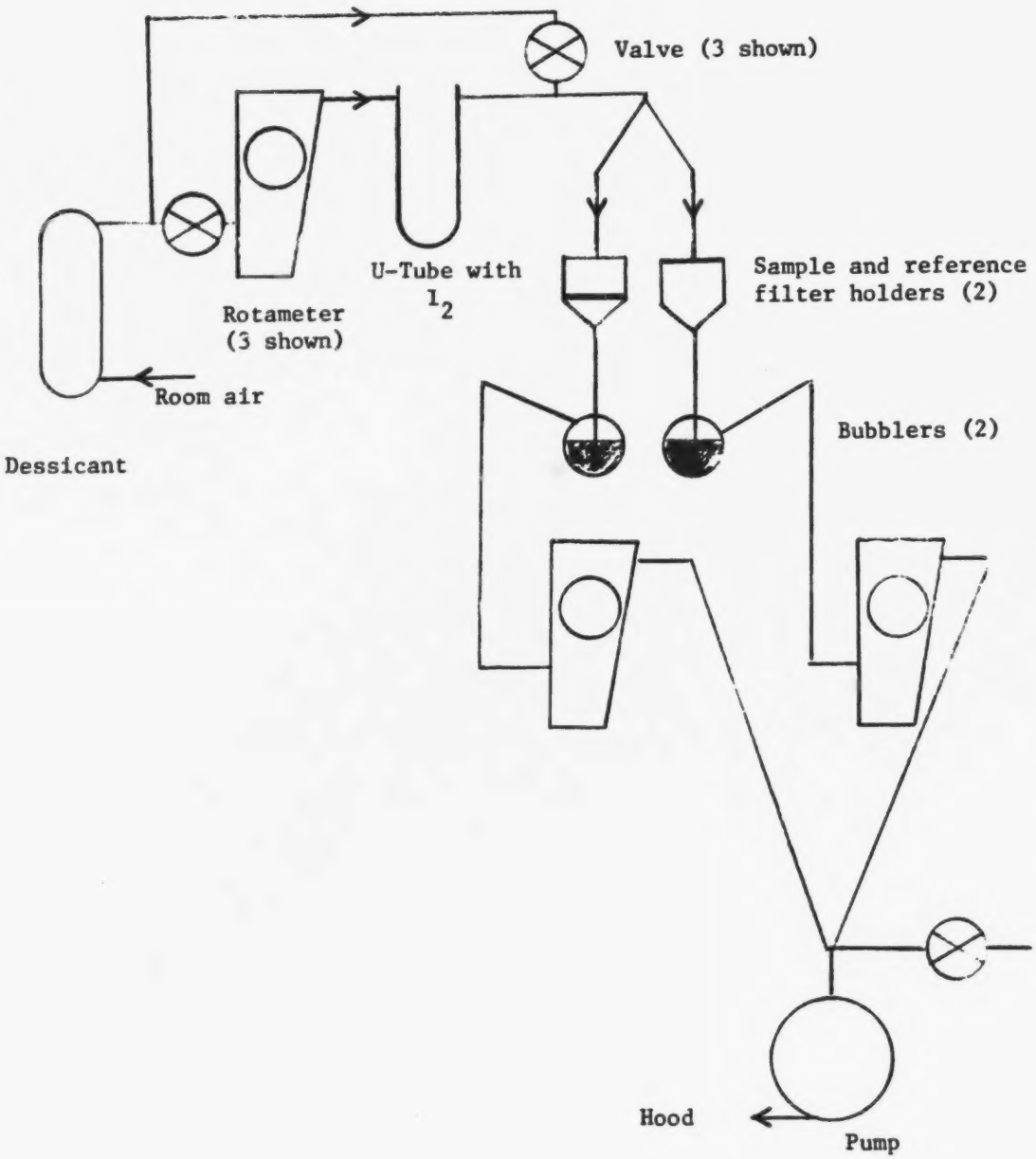

Figure 2.14. Set-up for I_2 experiments.

The analytical technique involved the use of a 2% w/w aqueous solution of KI and the measurement of ultraviolet light absorbance at 360 nm wavelength.

The bubblers and the rotameters monitoring them were similar, but not identical, so the early runs (day 1) and a few of the last runs(day 2) were used to calibrate them with respect to each other. The initial bubbler calibrations gave a proportionality constant between the readings in the "sampler" filter holder/bubbler/rotameter system of 1.33 times the readings in the "reference" system.

The bubblers captured virtually all the I_2 that entered them. This was determined by placing the two bubblers in series and passing the I_2/air mixture through them at the standard flow rate. The iodine level in the second of the two was below the limit of detection, meaning that a few percent or less penetrated the first to the second (which had levels roughly one hundred times the estimated limit of detection).

The flow through the 47-mm diameter filter holders was 1.0 liters per minute for each, giving a face velocity of 1.0 cm/s. The bed sheet material, when wetted, was first soaked in water or a 5% w/w baking soda solution, then the stack of six thicknesses was folded in half and in half again and pinched firmly to remove much of the water. The liquid uptake by the sheet discs was about 0.04 g, about half of which was still on them at the end of the tests.

I_2/Sheet Results

The penetrations (concentrations measured at the "filter" bubbler divided by expected concentrations, based on the "reference" bubbler concentrations) for six layers of sheet, dry, wet with water, and wet with 5% w/w solution of baking soda (sodium bicarbonate) are shown in Table 2.15. Their means and the 95-percent confidence interval (C.I.) limits on those means are shown as well. The bicarbonate-wetted sheets reduced the concentration by a factor of 5 to 10; the water-wetted sheets reduced it by a factor of 2 to 3; the dry sheet did not seem to reduce it appreciably.

I_2/Towel Tests

A set of experiments were run with the higher-quality towel. Since there was little evidence of I_2 collection by dry cotton material, the second set of tests was limited to wetted conditions, where the liquids were water (first) or the 5% w/w (5% by weight), solution of baking soda ($NaHCO_3$). A second set of calibrations with the bubblers gave a ratio of the "filter" concentrations when empty to the "reference" concentrations of 1.16 (standard deviation: 0.5; 95% C.I.: 0.64, 1.69), which was used for these data. (We could have used, instead, the mean of the ratios from the calibration from both sets of experiments, which was 1.26; with a 95% C.I. of 0.99, 1.53, shown in Figure 2.15.)

Table 2.16 shows the penetrations for the towel as wetted with water

TABLE 2.15. I_2/SHEET RESULTS

Fabric Condition	Penetration[a] Measured	Mean	Std. Dev.	95% C.I.
dry	.87	.99	.09	(.85, 1.13)
	1.06			
	1.05			
	1.00			
wet-water	.37	.45	.06	(.36, .54)
	.47			
	.46			
	.50			
wet-$NaHCO_3$ 5% w/w solution	.12	.15	.04	(.09, .21)
	.19			
	.17			
	.12			

a. Through six layers at 1.0 cm/s

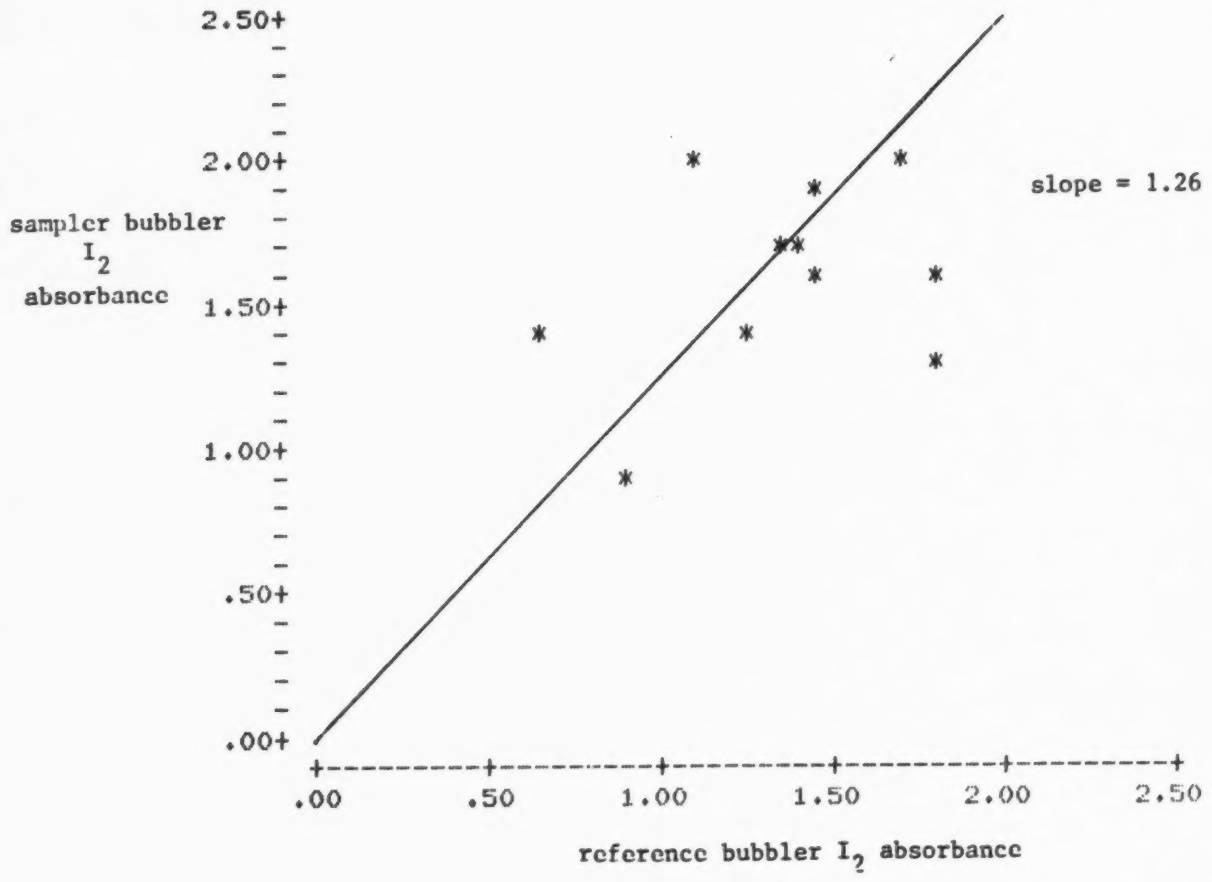

Figure 2.15. Initial and final calibration values for sample vs. reference bubblers.

TABLE 2.16. I_2/TOWEL RESULTS

Fabric Condition	Penetration[a] Measured	Mean	Std. Dev.	95% C.I.
wet-water	.30 .39 .42 .45	.39	.06	(.29, .49)
wet-$NaHCO_3$	.25 .32 .33 .33	.31	.04	(.24, .37)

a. Through two layers at 1.0 cm/s

(the mean being 0.39) and for the towel wetted with the sodium bicarbonate solution (the mean being 0.30). This suggests that the wetted towel reduced the concentration to one-third the initial level, whether wetted with water or with a baking soda solution. The toweling held 2 g of water, however, which would allow it to absorb several hundred μg of I_2 before being saturated. (The wetted handkerchief held only 0.04 g of water, which would be saturated with ~ 10 μg of I_2). This may explain the lack of a difference between the $NaHCO_3$ solution and distilled water results for the toweling.

I_2 Tests: Discussion

The statistical confidence limits treat the variability of the readings and the calibrations as though it is composed of random error only. In fact, we noted a tendency for the readings in either flow path to be low after the system was purged for several minutes with clean air, suggesting the uptake of I_2 by the surfaces (glass, steel, and about 1 cm of plastic tubing used to make connections). This means that the statistical errors are overstated but that there are systematic errors that have not been quantified. The mean penetrations are still our best estimates, however.

The concentration of I_2 in the gas was determined from the following equation:

$$c = qV/Q\eta \qquad (2.10)$$

in which c is the concentration of I_2 in the gas (μg/liter), q is the concentration of I_2 measured in the liquid (μg/cm^3), V is the volume of liquid in the sampler (cm^3), and η is the collection efficiency of the bubbler (η = 1.0). A representative value of the absorption readings was 1.0, corresponding to 10.6 μg/cm^3. The air flow was 1 L/min for 5 minutes, giving Q = 5 liters. The volume of liquid was 25 cm^3. Thus the I_2 gas concentration was typically about (10.6)(25)/(5)(1) or 53 μg/liter, about 5 ppm. This concentration is orders of magnitude higher than that expected in offsite areas in the event of a reactor accident. The penetration (as a fraction) through the fabric should be independent of concentration, if the mass transfer rate is diffusion-limited. When solubility or the capacity of the material to retain the I_2 becomes limiting, then penetration would depend on concentration (for a given duration), being less at the lower concentrations. The results with water and with baking soda solutions suggest that solubility or capacity is a limiting factor. Thus, in an accident situation, the wetted materials should be even better than these tests indicate at preventing the penetration of I_2 directly through the fabric (although some fraction could be expected to leak between the fabric and the skin).

Quality Factors for Gas Adsorption

From the foregoing one can calculate the quality factors for gas adsorption and absorption that are measured. The results are shown in

Table 2.17, in which the penetrations, pressure drops (estimated from earlier tests with the fabrics by multiplying the 1.5 cm/s pressure drops by 2/3), and quality factors are listed.

The penetration expected at a pressure drop of 100 Pa is

$$Pn(\Delta P = 100\ Pa) = \exp(-100\ q) \qquad (2.11)$$

For 100 q = 2.3 and 4.6, the penetration is 0.1 and 0.01, respectively. The following had 100 q > 2.3:

1. sheet or towel wetted with either water or baking soda solution, filtering I_2,

2. dry towel, filtering CH_3I, perhaps (see 95% C.I. for Pn, however).

In retrospect, more numerous layers of dry fabric could profitably have been tested.

Data Analysis: Fabric Flow Resistance

For low-velocity (actually, low-Reynolds-number) flow, the pressure drop across the fabrics should be proportional to velocity, becoming proportional to velocity squared as the velocity becomes very large. A useful generalization of our pressure drop data is obtained by using the quantity called "drag," the pressure drop per unit face velocity:

$$S = \Delta P/V \qquad (2.12)$$

which should become constant as the flow velocity approaches zero. Table 2.18 shows the drags ($(N/m^2)/(m/s)$) for single layers of the materials used, obtained by dividing the pressure drop (N/m^2) by the flow velocity (m/s) and by the number of layers. (The column headings end in "d" for dry or "w" for wet, start with "d" for drag, and indicate the fabrics in our usual manner.) The values for the dry fabrics are plotted in Figure 2.16, which makes it clear how similar were the sheet, shirt, handkerchief, and lower-quality towel. (The respirator values are "A" and the higher-quality towel values are "E" in that figure.) The values for the wet fabrics are plotted in Figure 2.17. (Here, "A" is for the sheet, "B" for the shirt, "C" for the towel, and "D" for the handkerchief.) The figures make it clear that there is definitely a trend toward increased drag as velocity increases. We used standard linear regression techniques to fit the drag values to the equation

$$S = \Delta P/V = a + bV \qquad (2.13)$$

and the results are shown in Table 2.19; the first column has the material; the second gives "a"; the third shows "b"; the fourth gives the standard error of the estimate of "b" (the standard deviation expected if "b" were estimated from many more sets of three measurements); the final column gives the coefficient of determination, R^2 (adjusted for the number of degrees of freedom). These values allow one to estimate the pressure drop for any face velocity within the range of our measurements

TABLE 2.17. MEASURED QUALITY FACTORS FOR VAPOR ADSORPTION OR ABSORPTION

Fabric (# Layers)	Condition	Vapor or Gas	Pn	Δp[a]	q
sheet (4)	dry	CH_3I	.90	7	0.015
sheet (6)	wet-water	I_2	.99	10	0.001
sheet (4)	wet-water	CH_3I	.87	21	0.0066
sheet (6)	wet-water	I_2	.45	32	0.025
sheet (4)	wet-$NaHCO_3$	CH_3I	.99	21	0.0005
sheet (6)	wet-$NaHCO_3$	I_2	.15	32	0.059
towel (1)	dry	CH_3I	.93	1.7	0.043
towel (1)	wet-water	CH_3I	1.00	7	0.0
towel (2)	wet-water	I_2	.39	15	0.063
towel (2)	wet-$NaHCO_3$	I_2	.31	15	0.078

[a] Estimated from earlier tests at 1.5 cm/s.

TABLE 2.18. DRAG ($(N/m^2)/(m/s)$) FOR DRY AND WETTED MATERIALS (SINGLE LAYER) AT .015, .05, .15 m/s.

DRY

sheet	lower-quality towel	shirt	handkerchief	higher-quality towel	respirator
166.000	166.000	228.250	232.400	581.000	1660.00
166.000	161.850	224.100	244.020	597.600	1593.60
168.767	178.450	242.775	260.620	630.800	1577.00

WET

sheet	shirt	handkerchief	higher-quality towel
622.500	435.750	975.40	1577.00
659.850	466.875	1095.60	1718.10
830.000	664.000	1460.80	2158.00

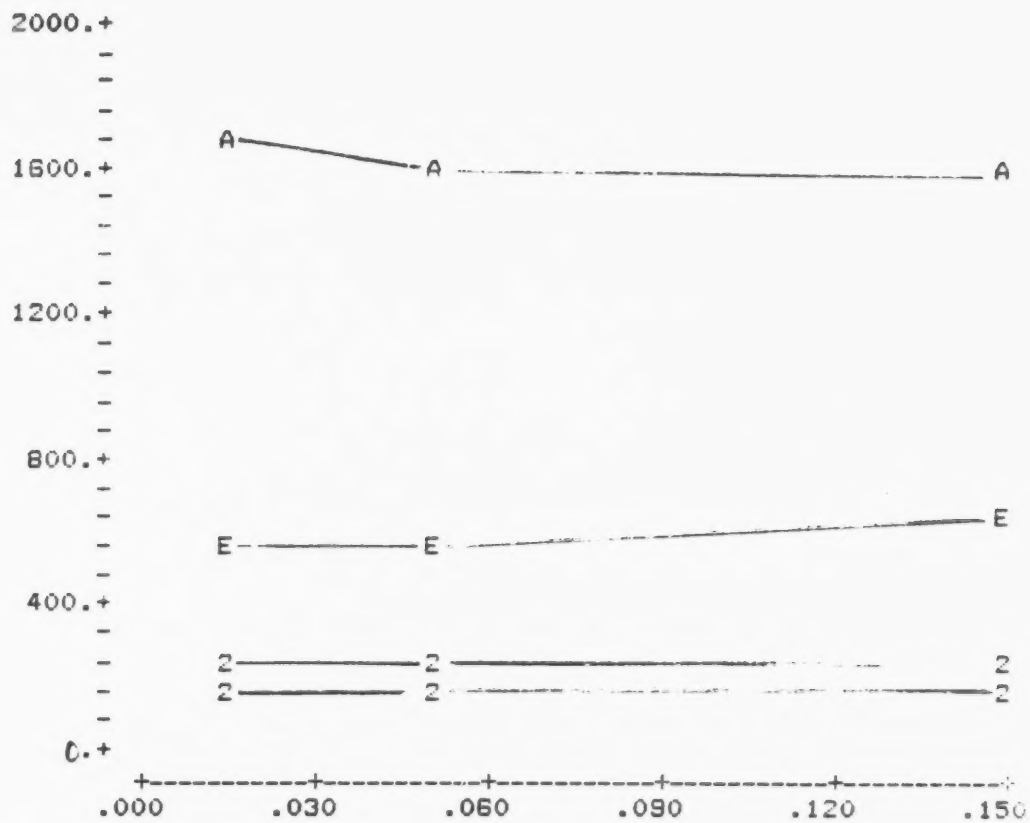

Figure 2.16. Drag (N-s/m^3) versus velocity (m/s) for dry materials (single layer). (A = respirator; E = higher-quality towel.)

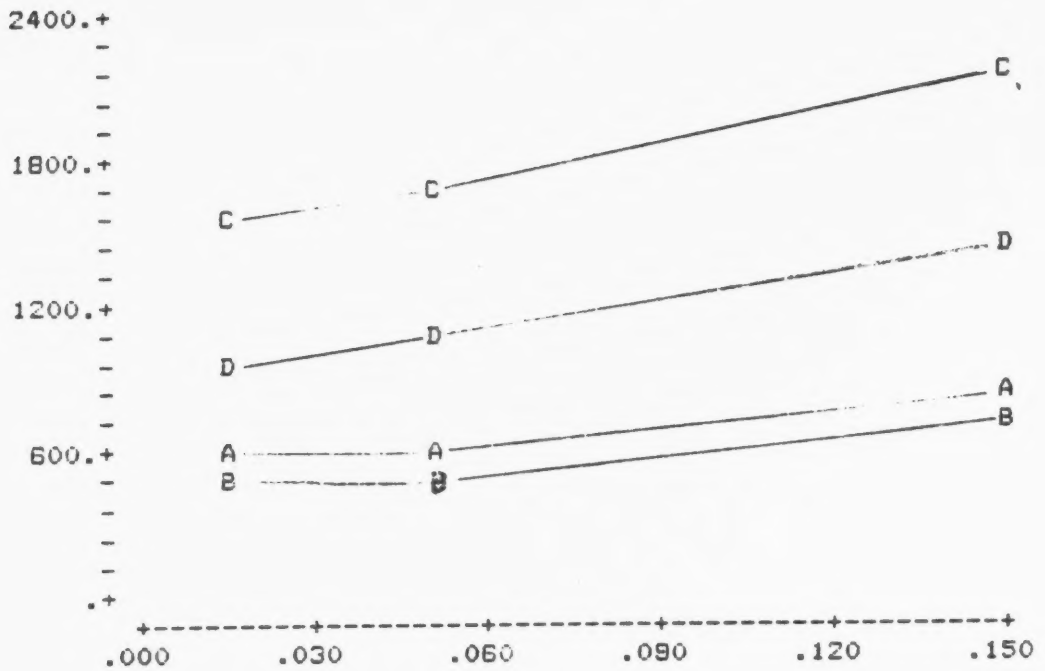

Figure 2.17. Drag (N-s/m^3) versus velocity (m/s) for wetted materials (single layer). (A = sheet; B = shirt; C = higher-quality towel; D = handkerchief.)

TABLE 2.19. REGRESSION RESULTS: DRAG VERSUS VELOCITY

Fabric	a	b	SE(b)	R^2_{adj}
		DRY		
respirator	1647	-516	356	.35
sheet	165	22	6	.88
shirt	223	125	63	.60
towel	161	109	59	.55
towel.2	577	361	29	.99
handkerchief	231	200	34	.94
		WET		
sheet	591	1573	131	.99
shirt	397	1753	223	.97
towel.2	1508	4325	76	1.00
handkerchief	922	3585	68	1.00

for these fabrics. The values for the shirt, sheet, and handkerchief suggest that the drag for such cotton fabrics when dry is about 200 + 100 V $(N/m^2)/(m/s)$. The regressions show a velocity dependence for all the wet fabrics and for the dry sheet, high-quality towel, and handkerchief.

Table 2.20 gives the ratios of the wet drag to the dry drag for the fabrics tested, and these ratios are plotted against velocity in Figure 2.18. ("A" is for the sheet, "B" for the shirt, "C" for the higher-quality towel, "D" for the handkerchief.) At the lower velocities, the drag is typically 2 to 5 times the drag of the dry material (once the material has come into quasi-equilibrium).

TABLE 2.20. WET/DRY DRAG RATIOS FOR .015, .05, .15 m/s.

sheet	shirt	handkerchief	higher-quality towel
3.75	1.90	4.21	2.71
3.57	2.08	4.48	2.87
4.91	2.73	5.60	3.42

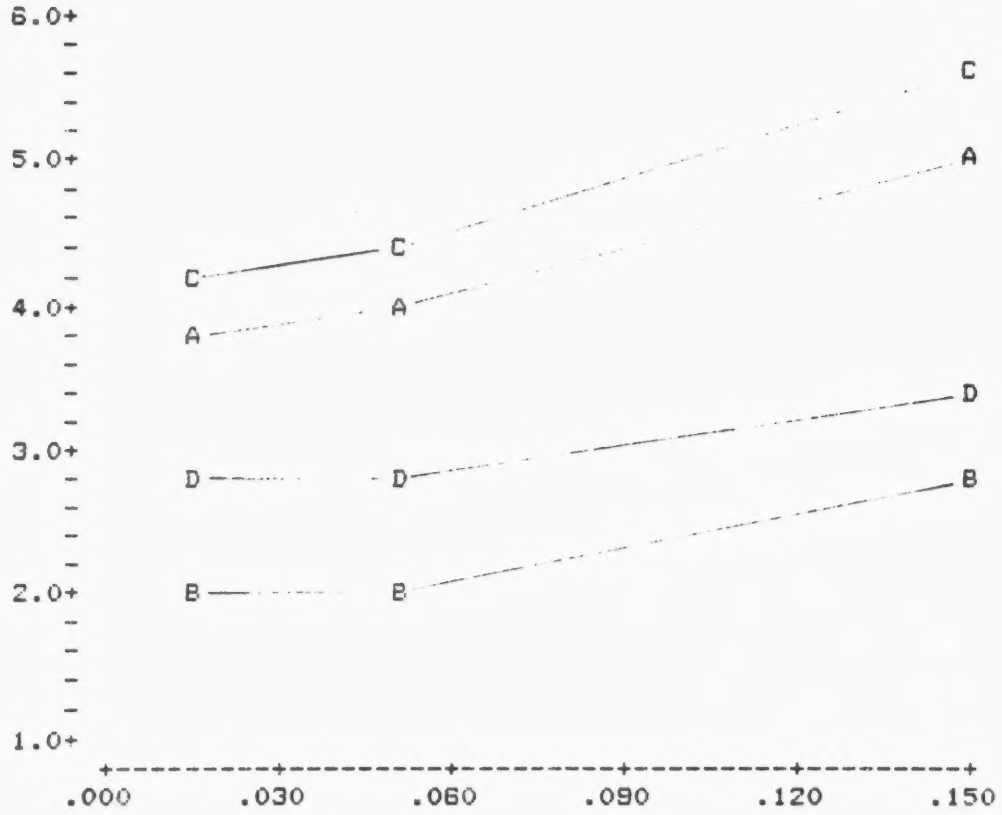

Figure 2.18. Wet/dry drag ratios versus velocity (m/s). (A = sheet; B = shirt; C = higher-quality towel; D = handkerchief.)

SECTION 3

MATHEMATICAL MODELING

INTRODUCTION

The two principal elements in the mathematical modeling effort were the development of a computer model for cloth filtration and the extension of a figure of merit, the "quality factor," to the most basic filtration level, the isolated fiber, as an aid in understanding (and designing) cloth filters.

CLOTH FILTRATION MODEL

The FORTRAN program computer model of cloth filtration developed in this study is printed in Appendix A, along with its output for a specific case, described below. The cloth is viewed as having three types of cylindrical collectors: warp yarns, woof yarns, and "loose" fibers associated with these yarns. We assume that the probability of a particle's capture by one collector is independent of the probability of its capture by the other collectors, for each of these collector types, so that we calculate the probability of escape (penetration) through the warp yarns, through the woof yarns, and through the fibers, then multiply these probabilities to get the total probability of penetration, treating warp, woof, and fibers as separate layers.

The inputs are the fractional cross-sectional areas (FAREA) of the three types of collectors (currently, the warp yarns are assumed to cover 50 percent of the area, the woof yarns 50 percent, and the loose fibers 5 percent, probably low estimates for the warp and woof), the diameters of the collectors (DC = 100 μm, 200 μm, and 10 μm), the length per unit area (1 m^2) of cloth (FLENGTH = 5000 m, 2500 m, 5000 m), the particle diameters of interest (DP), their characteristic aerodynamic times (TAU) and diffusion coefficients (DIFCO), and the face velocity (UFACE, corrected for porosity) and velocity at infinity (UINF).

Single-collector collection efficiencies (area cleaned per collector cross section) are calculated for each collector type by subroutines for impaction (IMPN), interception (INTN), diffusion (DIFFN), and gravitation (GRAVN), and these are printed and stored for the three fiber types (warp, woof, loose) and the ten particle sizes. The single-mechanism, single-collector collection efficiencies are then combined by two methods, using the subroutine EFFC: they are summed (ESUM), as an upper estimate, and only the largest is used (EMAX), as a lower estimate. These two estimates are then passed to the subroutine PN, which estimates the collection efficiency of each collector type array by multiplying the single-collector efficiency of that type of collector by its fractional cross-sectional area. One minus the collection efficiency is the penetration for the array and the total penetration for one layer of cloth is the product of the penetrations through the arrays. The flow resistance is calculated by summing the forces on all the cylin-

ders, as calculated with the subroutine DRAG, using the flow per unit area divided by the fraction of open area (UFACE). DRAG treats the cylinders as isolated, and the drag predicted by this method is somewhat too low.

Table 3.1 gives the equations used to calculate single-fiber collection efficiency.

Results of our simulations with this hypothetical fabric are shown in Figures 3.1 to 3.7.

Figure 3.1 shows the logarithm of the single-collector impaction efficiency (eimp) versus the logarithm of the particle diameter (pdiam). For 30-μm-diameter particles, each collector type had a single-collector efficiency of 1.00. For 10-μm particles, only the smaller yarn and the fibers had impaction parameters greater than the critical value for collection (0.8), so the other yarn had zero collection efficiency by the impaction mechanism. Particles of 5 μm were also collected by impaction, but those of 2 μm and less were not.

Figure 3.2 shows the logarithm of the single-collector interception collection efficiency versus the logarithm of the particle diameter. (Two values are not plotted: the collection efficiency became greater than 1.00 for particles larger than the smallest collector diameter (10 μm) and became less than 10^{-5} for the smallest particles and the biggest collector.)

Figure 3.3 shows the logarithm of the single-collector diffusion collection efficiency versus the logarithm of particle diameter. The particles of 10^{-9} m diameter have been chosen to simulate the collection of a gas which is not re-emitted by the fibers: the diffusivity of these particles is 5×10^{-6} m^2/s, the same order of magnitude as the diffusivity of molecules of iodine and of methyl iodide. Note that for these smallest "particles," the collection efficiencies for these collectors can be greater than one: diffusion to the surface allows the collectors to "sweep" a cross-sectional area greater than their own.

Figure 3.4 shows the logarithm of the single-collector collection efficiency for gravitation versus the logarithm of particle diameter. This is determined wholly by the ratio of the particle's settling velocity to the flow velocity, so each collector type has the same efficiency, an efficiency which becomes significant for particles 10 μm and larger.

Figure 3.5 shows the logarithm of the sum of the single-collector efficiencies versus the logarithm of the particle diameter. It shows the characteristic minimum in the vicinity of 0.3 μm which has been observed widely in theoretical and experimental filtration studies.

Figure 3.6 shows the logarithms of the penetrations predicted by the model for sixteen thicknesses of such cloth. For Figure 3.6, the penetration was calculated two ways: (A) from the lower estimate of collection

TABLE 3.1. SINGLE-FIBER COLLECTION EFFICIENCY EQUATIONS

Mechanism	Equation	Source
Impaction[a]	$\eta_I = 1 - 0.8/\psi$, $\psi > 0.8$	(Brown, 1980)
	$\eta_I = 0$, $\psi < 0.8$	
Interception[b]	$\eta_{RV} = (d/D)^2/(2.00 - \ln Re)$, $Re \ll 1$	(Fuchs, 1964)
	$\eta_{RP} = (1+d/D) - 1/(1+d/D)$, $Re \gg 1$	
Diffusion	$\eta_D = 2.7(D^*/vD)^{2/3}$	(Cheng and Yeh, 1980)
Gravitation[c]	$\eta_G = G/(1 + G^2)^{\frac{1}{2}}$	(Iinoya and Orr, 1977)

a. $\psi = \tau v/D$, $\tau = c\rho_p d^2/18\mu$

b. $Re = \rho vD/\mu$ and the program chooses η_{RV} or η_{RP} depending on $Re \gtrless 1$.

c. $G = g\tau/v$.

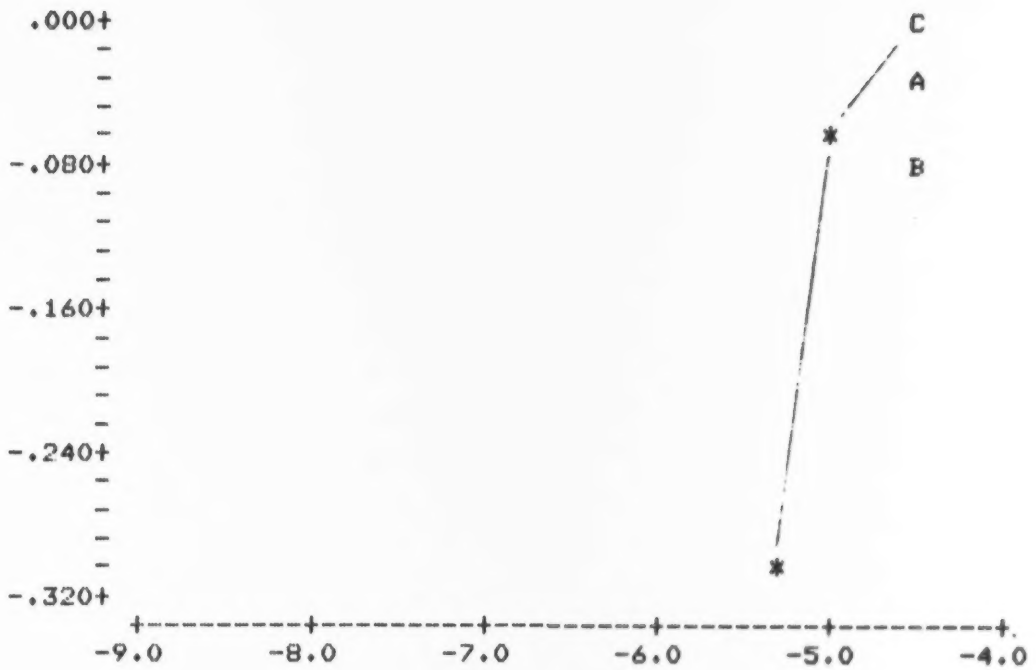

Figure 3.1. Logarithm of the single-collector impaction efficiency (eimp) versus the logarithm of the particle diameter (pdiam). (Fiber diameters: A = 100 μm; B = 200 μm; C = 10 μm.)

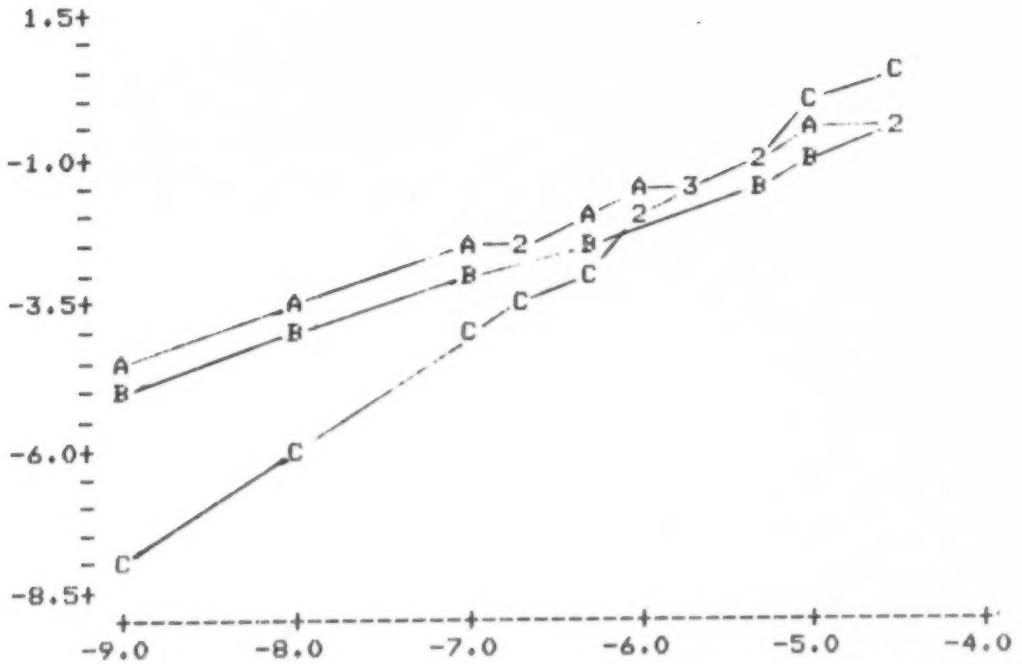

Figure 3.2. Logarithm of the single-collector interception collection efficiency versus the logarithm of the particle diameter. (Fiber diameters: A = 100 μm; B = 200 μm; C = 10 μm.)

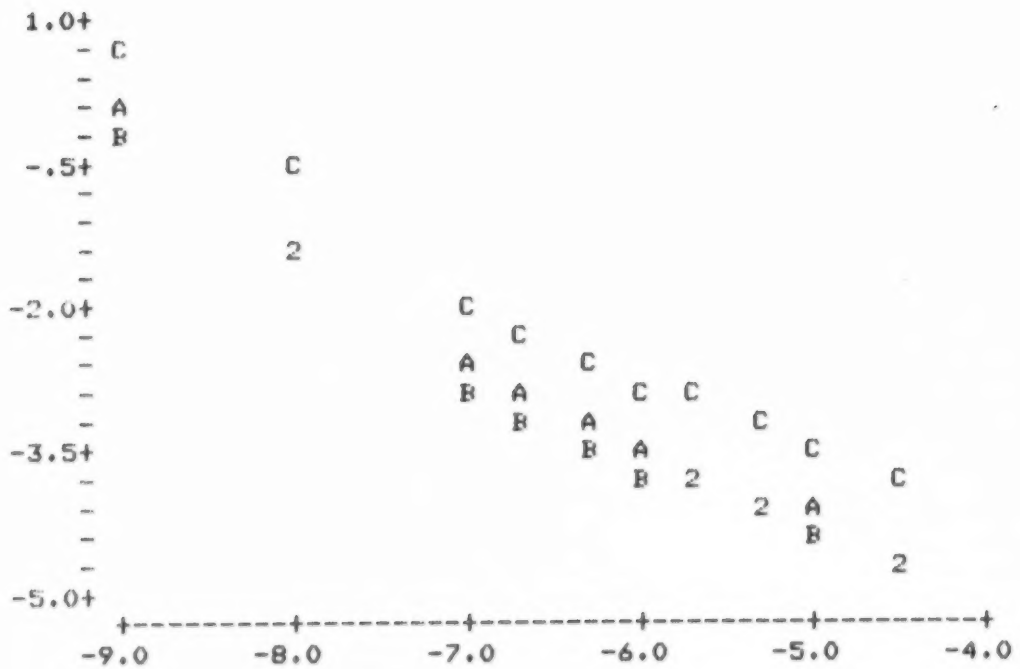

Figure 3.3. Logarithm of the single-collector diffusion collection efficiency versus the logarithm of particle diameter. (Fiber diameters: A = 100 μm; B = 200 μm; C = 10 μm.)

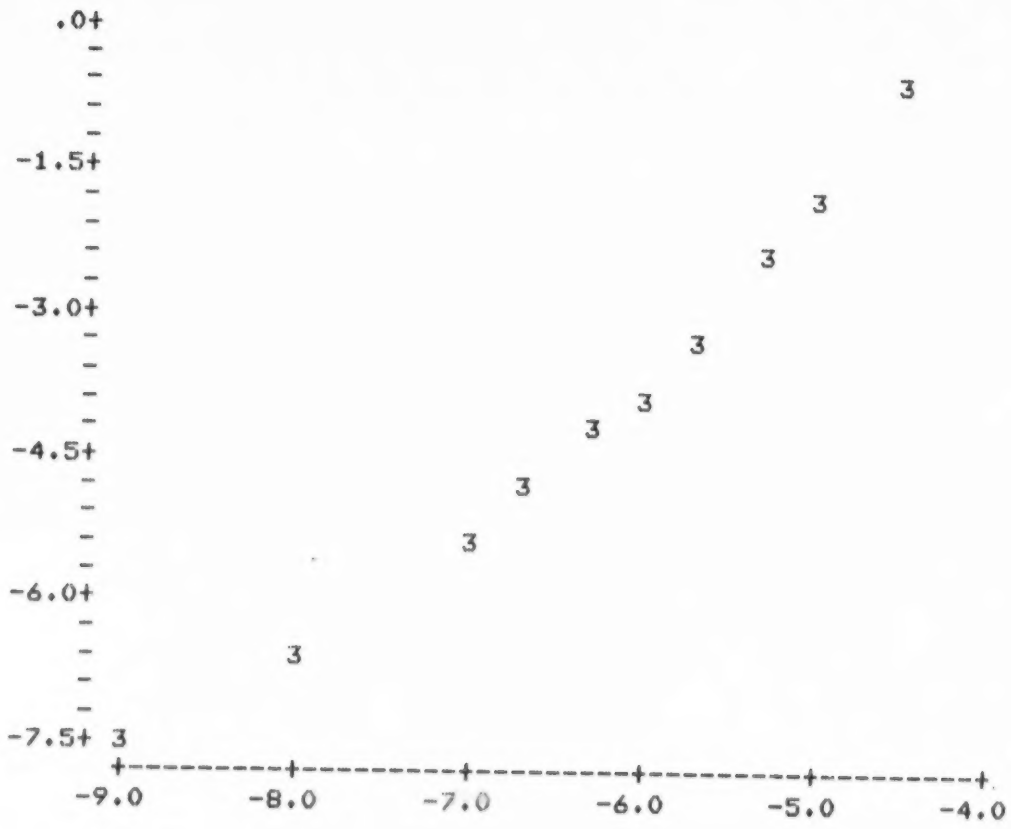

Figure 3.4. Logarithm of the single-collector collection efficiency for gravitation versus the logarithm of particle diameter.

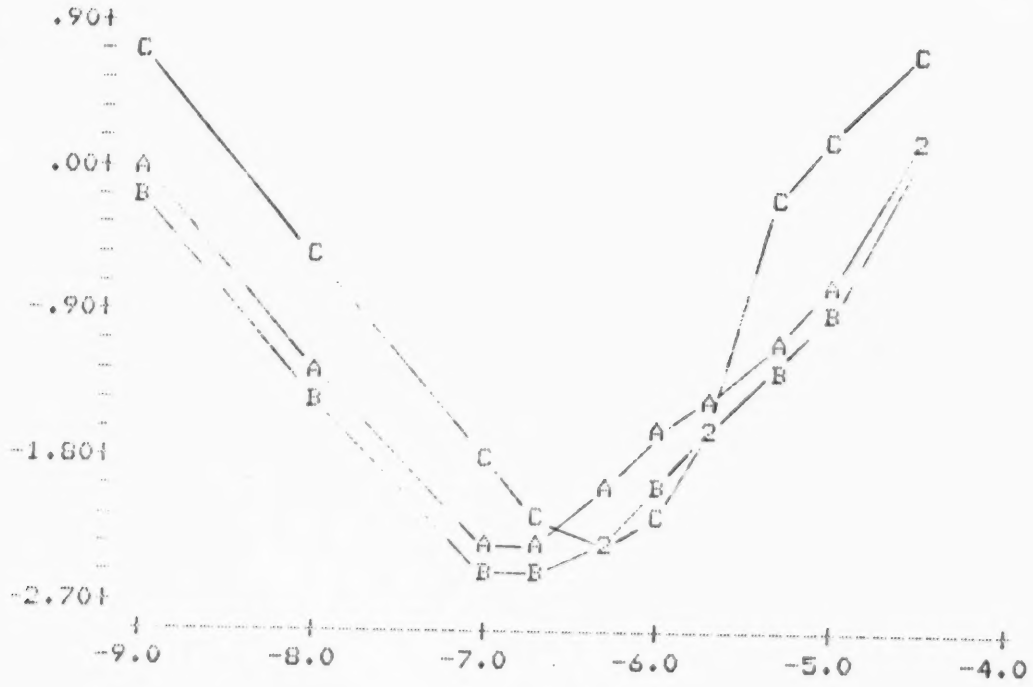

Figure 3.5. Logarithm of the sum of the single-collector efficiency versus the logarithm of the particle diameter. (Fiber diameters: A = 100 μm; B = 200 μm; C = 10 μm.)

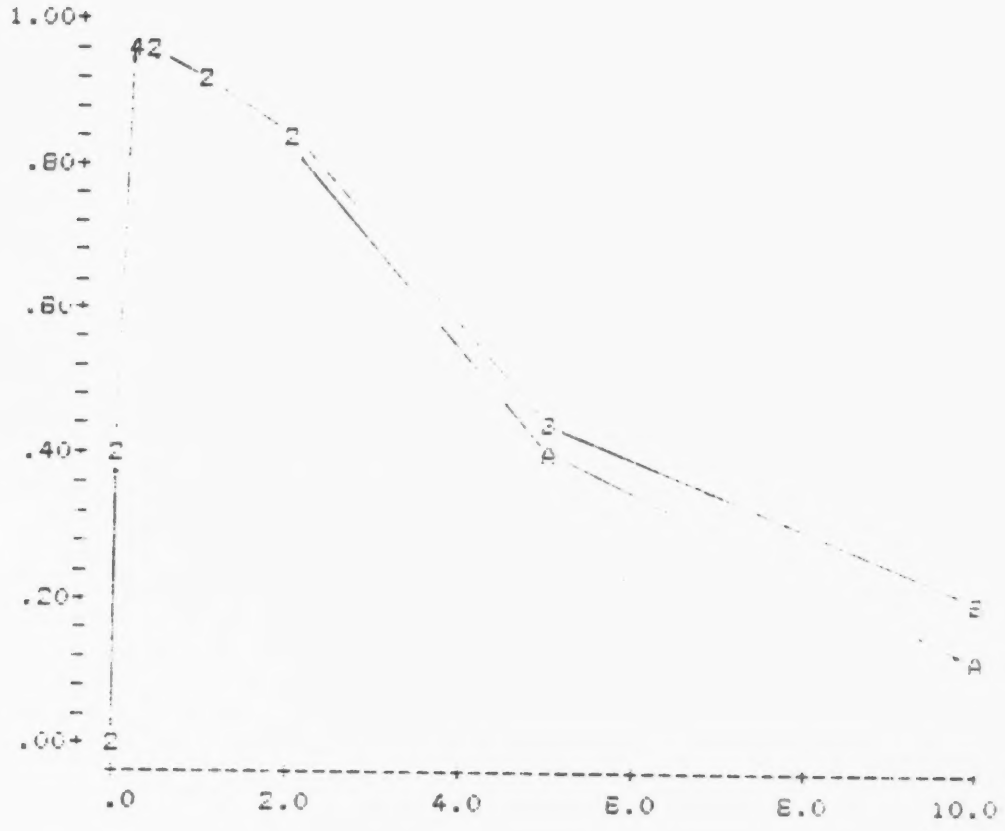

Figure 3.6. Penetration versus particle diameter (μm) predicted by the model for sixteen thicknesses of cloth. (A = ESUM; B = EMAX).

efficiencies, that for which the efficiency was not summed over the mechanisms, but rather the efficiency (for a given particle size) was chosen as the largest single efficiency (EMAX); (B) from the mechanisms summed (ESUM) for an upper estimate of collection efficiency, thus a lower estimate of penetration. Note that this rather open hypothetical cloth is predicted to have essentially zero penetration by the gases (pdiam = -9) if they are adsorbed or absorbed by the fibers rather than reflecting off them without capture. Note, also, that penetrations decrease strongly as functions of particle diameter for particles 2 μm and larger. (Numbers in the graph signify that more than one value occurred at that plotting position.)

PREDICTIONS BASED ON PENETRATION MEASUREMENTS

A short program was written (in BASIC) to calculate the penetration (by number or by mass) of aerosols having log normal size distributions, when flowing through the fabrics we tested. The program performs essentially the trapezoidal rule integration (Isaacson and Keller, 1966) of the equation

$$Pn = \int_0^\infty f(d)p(d)dd \qquad (3.1)$$

in which f(d) is the particle size distribution (by number or by mass) and p(d) is the penetration for particles of size d. The program is given in Table 3.2. (Trapezoidal rule integration was chosen so as not to require equal intervals of d.) If the number median diameter is specified, the result is the penetration by number. If the mass median diameter is specified, the result is mass penetration. The values of p(d) were those determined by our experiments with the NIOSH-approved respirator. Table 3.3 contains one of the sets of results we obtained from the program, in this case for an aerosol with a median diameter of 2 μm and a geometric standard deviation of 2, a plausible aerosol from a reactor accident. The table shows the size interval, its upper diameter limit, the value for f(d), the value for p(d), and the penetration of particles of size d and smaller. Note that the particles larger than 2 μm contribute negligibly to the cumulative penetration here. Table 3.4 contains the results of similar numerical experiments for a variety of median diameter and geometric standard deviation combinations. Special attention should be given to the combinations with median diameters 2.1 or 1.28 and geometric standard deviation of 1.5, as the aerosols used by Guyton et al. were reported to have mass median diameters of 2.1 μm and thus had number medians of 1.28 μm, for the reported geometric standard deviations, 1.5. (Because the impactors used by Guyton et al. tend to give the size distribution an artificial spread in size, the geometric standard deviation of the true particle sizes may have been substantially smaller, however.) For the aerosol size parameter combinations studied, the respirator would have removed from almost 90 percent to more than 99 percent of the particle mass/number. For an aerosol having a 2 μm mass median diameter and a geometric standard deviation of 2, the penetration of the respirator would be only about 4 percent by mass, which is comparable to the leakage around such a device in normal use. Therefore, even with penetration and leakage, the respirator would be expected to reduce the inhaled mass of this aerosol by a factor of ten.

TABLE 3.2. PROGRAM: LOG NORMAL AEROSOL PENETRATIONS

```
10   REM TRAPEZOIDAL RULE INTEGRATION OF LOG NORMAL DISTRIBUTION
20   REM OF MEDIAN DIAMETER M AND GEOM. STD. DEVN. G
25   REM OVER NINE SELECTED PARTICLE SIZES
38   REM USING NMD GIVES FRACTIONAL NUMBER PENETRATION
39   REM USING MMD GIVES FRACTIONAL MASS PENETRATION
40   REM THIS IS INTEGRATED WITH THE PENETRATION MEASURED, P(D(I))
50   LET D(1)=0.41
60   LET D(2)=0.58
70   LET D(3)=0.88
80   LET D(4)=1.4
90   LET D(5)=1.9
100  LET D(6)=2.3
110  LET D(7)=3.2
120  LET D(8)=4.8
130  LET D(9)=6.2
140  REM EVALUATION OF F(D) THE FRACTIONAL SIZE DISTRIBUTION
142  PRINT "MEDIAN DIAMETER, BY NUMBER OR MASS"
144  INPUT M
146  PRINT "GEOMETRIC STANDARD DEVIATION"
148  INPUT G
150  FOR I=1 TO 9
160  LET A=(LOG(D(I)/M))^2
165  LET A=A/(2*(LOG(G))^2)
170  LET B=LOG(G)*SQR(2*3.1416)
180  LET F(I)=EXP(-A)/(B*D(I))
190  NEXT I
200  REM INITIALIZE PENETRATION VALUES, USUALLY DATA
210  REM PENETRATION FOR RESPIRATOR AT 5 CM/S
211  LET P(1)=.268
212  LET P(2)=.216
213  LET P(3)=.103
214  LET P(4)=.043
215  LET P(5)=.010
216  LET P(6)=.000
217  LET P(7)=.006
218  LET P(8)=.000
219  LET P(9)=.000
240  REM TRAPEZOIDAL INTEGRATION
245  LET S=0.5*F(1)*P(1)*D(1)
248  PRINT "INTERVAL  UPPER DIAMETER  FREQUENCY  PENETRATION  CUM PENETRATION"
250  FOR I=1 TO 8
260  LET S=S+0.5*(F(I)*P(I)+F(I+1)*P(I+1))*(D(I+1)-D(I))
270  PRINT I,D(I+1),F(I+1),P(I+1),S
280  NEXT I
290  END
```

TABLE 3.3. SAMPLE RESULTS OF PROGRAM (MEDIAN = 2, GSD = 2)

Interval	Upper diameter	Frequency	Penetration	Cum Penetration
1	.59	.201418	.216	.011692
2	.88	.32432	.103	.0232287
3	1.4	.360129	.043	.0359402
4	1.9	.302084	.01	.0405869
5	2.2	.245204	0	.0411711
6	3.2	.14292	6.00000e-03	.0415569
7	4.6	.0540034	0	.042243
8	6.2	.0244969	0	.042243

TABLE 3.4. SUMMARY OF CALCULATIONS FOR LOG NORMAL AEROSOLS

particle median diameter	geometric standard deviation	penetration
10.0000	3.00000	.005000
5.0000	3.00000	.019000
2.1000	1.50000	.018000
2.0000	5.00000	.060000
2.0000	4.00000	.063000
2.0000	3.00000	.061000
2.0000	2.00000	.042000
2.0000	1.50000	.021000
1.9000	1.10000	.010000
1.4000	1.10000	.066000
1.2800	1.50000	.064000
1.0000	3.00000	.105000
.5000	3.00000	.119000
.4100	3.00000	.116000

We analyzed the data from Guyton et al. in terms of the quality factor:

$$q = (1/\Delta P)\ln(Pn) \qquad (3.2)$$

and Table 3.5 shows the pressure drop (1 mmH_2O = 10 Pa), the measured efficiency, and the quality factor. Recall that a quality factor of .023 or more means the penetration is 0.10 or less at 10 mmH_2O = 100 Pa, considered an acceptable pressure drop for breathing. The materials with $q \geq 0.023$ were:

bath towel	(q = 0.027)
bath towel (wet)	(q = 0.040)
woman's cotton handkerchief	(q = 0.040)

Figure 3.7 shows these values as quality factor versus pressure drop. We believe the major reason for the decrease in quality factor as the pressure drop increased was the leakage around the material, not the penetration through it. This underscores the importance of keeping the pressure drop as low as practicable, in application to expedient respiratory protection, for both protection and comfort.

Design Optimization: Cloth Filter for Aerosols

The area of the fabric covering the face will be pretty well fixed by practical considerations as $A \sim 10^2 cm^2$ and the flow velocity will be $v \sim 1$ cm/s. Fabric thickness, geometry, and fiber sizes will determine pressure drop and penetration, and we look to minimize penetration at a given pressure drop (such as 10 mmH_2O = 100 N/m^2). We have proposed to extend to individual fibers the concept of the quality factor.

$$q'' = \eta/(F/A) \qquad (3.3)$$

in which η is the collection efficiency for a single fiber (due to a particular mechanism, on particles of a given size) and (F/A) is the drag force on the fiber, divided by its area. Maximizing q" with respect to fiber diameter (D) should maximize collection (minimize penetration) at a given pressure drop, other things being equal.

Table 3.1 presented a summary of equations selected from the aerosol literature for collection efficiency for fibers. The force per unit area on the collector is related to the drag coefficient by:

$$C_D = (F/A)/(1/2)\rho v^2 \qquad (3.4)$$

and a useful approximation to C_D can be obtained from

$$C_D = a/Re^b \qquad (3.5)$$

This results in the following equation for the quality factor for a single fiber:

$$q'' = \eta Re^b/(a/2)\rho v^2. \qquad (3.6)$$

TABLE 3.5. SINGLE-COLLECTOR EFFICIENCY (η) AND QUALITY FACTOR(q'') FOR v = 1 cm/s, D = 1 μm, d = 1 μm

Mechanism	Efficiency Formula(η)	Efficiency (η)	Quality factor ($q'' = \eta D/6\ \mu v Re^{0.2}$)
Impaction	$(1 - 0.8\ D/\ v)$ or zero	0 ($\tau v/D = 0.036$)	0
Interception	$(d/D)^2/(2.00 - \ln Re)$	.11	.042
Diffusion	$2.7(D^*/vD)^{2/3}$	0.053	0.021
Gravitation	$g\tau(1 + (g\tau)^2)^{\frac{1}{2}}$	0.0035	1.4×10^{-4}

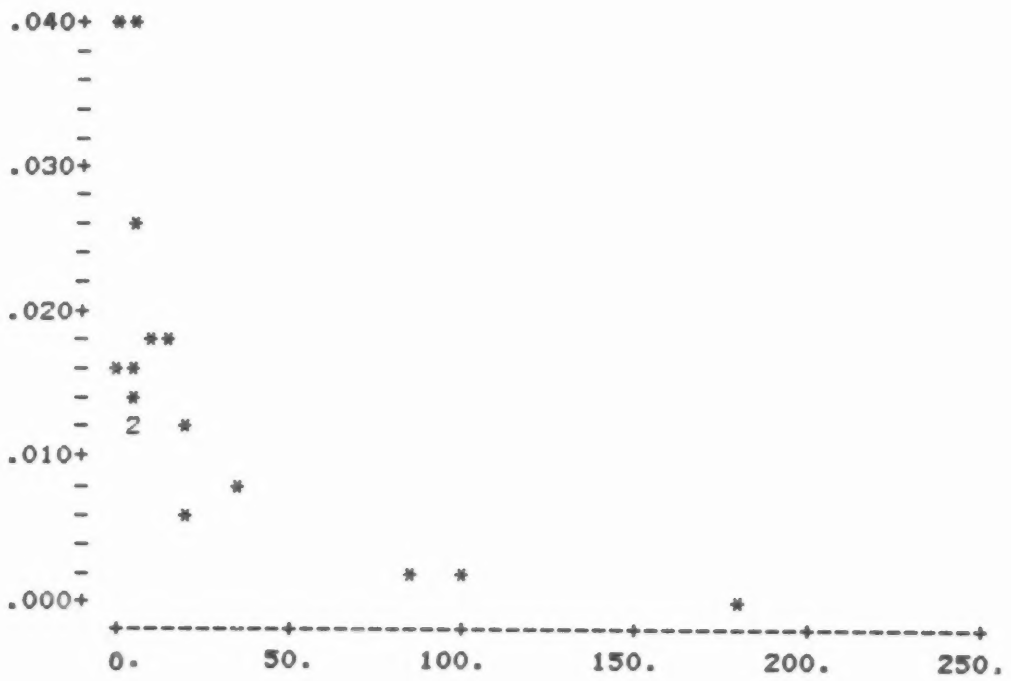

Figure 3.7. Quality factor vs. pressure drop (mm H_2O): Guyton et al. data.

The Reynolds number is

$$Re = \rho vD/\mu, \tag{3.7}$$

which for air at NTP flowing at 1 cm/s past a 1-μm diameter fiber is 7×10^{-4}, the Stokes (viscous flow) regime, for which

$$C_D \doteq 12/Re^{0.8} \tag{3.8}$$

making

$$q'' \doteq \eta D/6\ \mu v Re^{0.2}. \tag{3.9}$$

Table 3.5 has equations for this flow regime for the collection efficiency due to impaction, interception, diffusion, and gravitation (generally the major potential mechanisms for collection of electrically neutral particles).

The diffusion efficiency equation is related to the particle diffusivity (D*), which itself is proportional to temperature and inversely proportional to particle diameter (approximately).

The gravitational efficiency depends only on the settling velocity (the acceleration of gravity times the characteristic time).

We can show that the impaction quality factor is maximized when $\tau v/D \doteq 1$, and for the assumed v and D that means d = 5 μm.

The interception quality factor is the greatest, and it increases as D^{-1} approximately, meaning that finer fibers are better.

The diffusion efficiency is small, but the quality factor will increase as $D^{1/3}$.

The gravitational efficiency is negligible, though its quality factor would be proportional to D.

Whichever equation we use to estimate the collection efficiency due to interception, it predominates for particles around 1 μm in diameter, although impaction will predominate for particles of $d \gtrsim 10$ μm.

An example will show the use of the quality factor approach in the design of a face mask. We assume a volume flow per unit area of v = 0.01 m/s for a mask area of about 100 cm^2. Although an approximate expression for the drag coefficient for a cylinder is $12/Re^{0.8}$, the calculation can be done more exactly using (Batchelor, 1967):

$$C_D = 8\pi/Re(2.0 - \ln Re) \qquad \text{for } Re < 0.1 \tag{3.10}$$

and (Clift et al., 1978):

$$C_D = 9.689\ Re^{-0.78}(1 + 0.14\ Re^{0.82}) \qquad 0.1 \leq Re \leq 5 \qquad (3.11)$$

These equations for C_D were used (for air at room temperature and atmospheric pressure) with the equations above for the collection efficiencies due to diffusion, interception, gravitation, and impaction, to study the quality factors for fibers of diameters from 10^{-6} m to 10^{-2} m. The results for particles of 1 μm diameter and the density of water are shown in Figure 3.8. In Figure 3.9 are the results for a particle of diameter 0.1 μm.

As shown in Figure 3.8, at this relatively low velocity, the 1 μm particle is captured most efficiently by diffusion for the smaller fiber sizes and most efficiently by gravitational settling for the larger fibers. As fiber size increases, gravitational settling efficiency is unchanged, but the force per area decreases. The decrease in diffusive collection is nearly balanced by the decrease in force per area but the decrease in interception efficiency is greater than the decrease in force per area.

In Figure 3.9 the dominance of diffusion for the 0.1 μm particle is evident, although the quality factor does not change strongly with fiber diameter. Interception and gravitational settling quality factors have both decreased in proportion to the square of the particle diameter, as diffusion increased roughly in proportion to the particle diameter.

Neither for the 0.1 μm particles nor for the 1.0 μm particles did impaction become appreciable at this low velocity, and gravitational settling is surprisingly important for the larger of the two particles. For particles 10 μm in diameter, at v = 0.01 m/s, the mechanism of interception gives the highest quality factor for fibers of 1 μm and 3 μm diameter; gravitation becomes most important for fibers 10 μm in diameter and larger. (As velocity is increased, however, interception and impaction come to dominate for particles 1 μm and larger.)

This analysis shows, somewhat surprisingly, that if fibers larger than about 1 μm in diameter are to be used, the face mask will have its lowest flow resistance at a given level of collection efficiency (at this velocity, 0.01 m/s) if the fiber diameter is made as large as is practical, considering such factors as weight and manufacturability.

Such analyses can be used to help design expedient respiratory protection. For determining the number of layers of material to use, one estimates the surface area covered (A) (typically about 10^2 cm^2) and the flow velocity (volume flow rate (Q) of 10 to 30 liters per minute divided by the area and divided by the fraction (f) of the time breathing is occurring). The product of the flow velocity and the drag is the pressure drop (ΔP) for a single layer. One might use as many layers as possible up to a pressure drop of about 100 N/m^2 (1 cm of water). The product of the pressure drop and the quality factor (q) for the material at the velocity is the negative natural logarithm of the penetration for the particle size under consideration. In order, the key equations are:

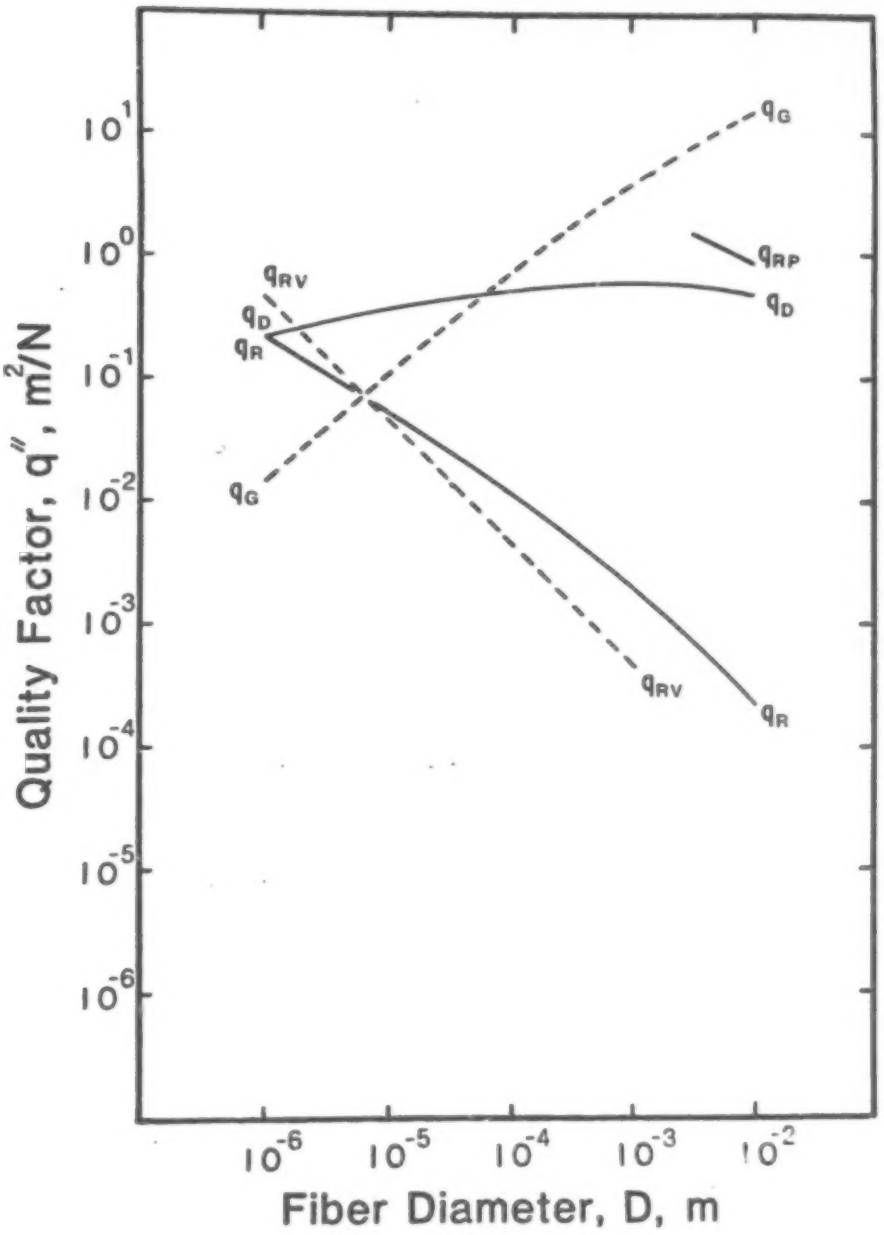

Figure 3.8. Quality factors for collection of particles of 1 μm diameter and having the density of water, at a velocity of 1 cm/s, for fiber diameters from 1 μm to 1 cm.

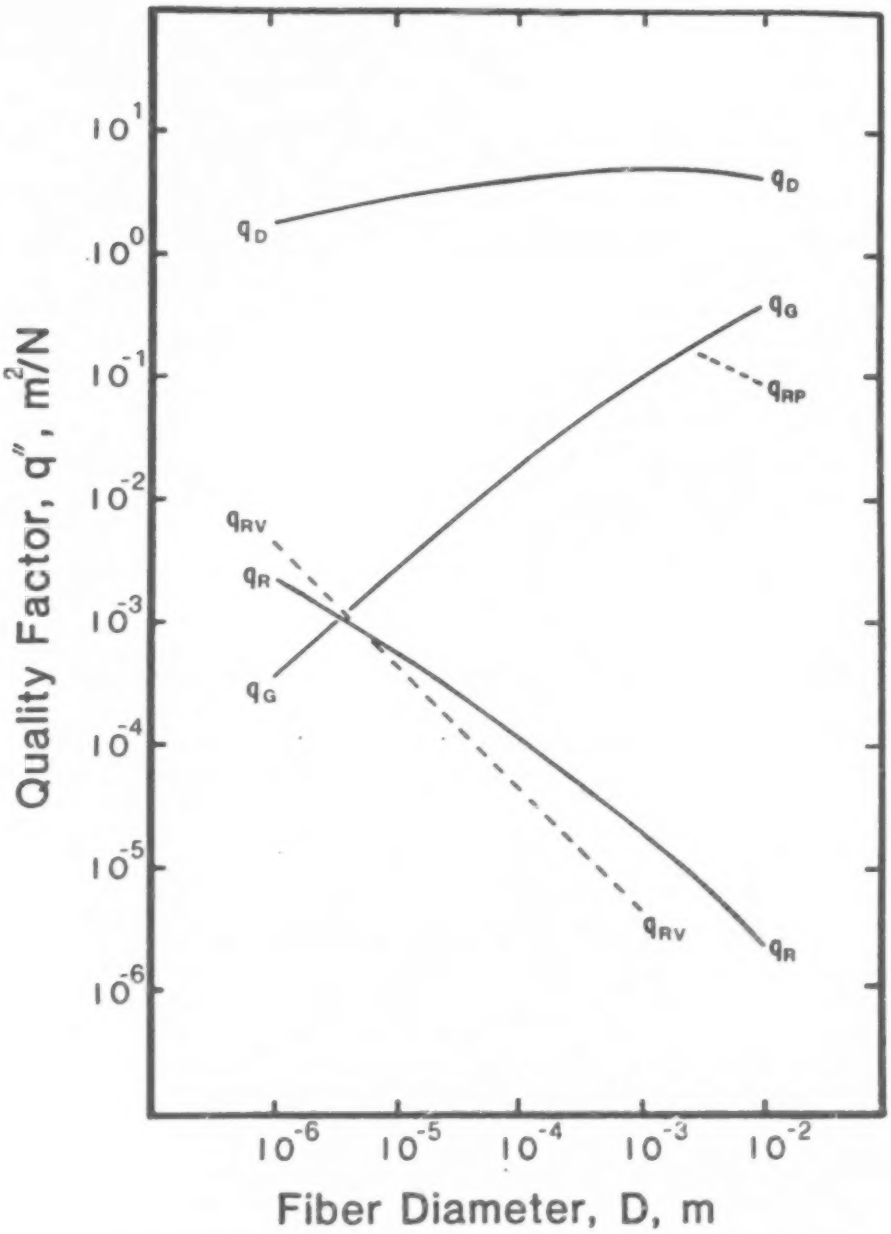

Figure 3.9. Quality factors for collection of particles of 0.1 μm diameter and having the density of water, at a velocity of 1 cm/s, for fiber diameters from 1 μm to 1 cm.

$$V = Q/Af \tag{3.12}$$

$$\Delta P = (S)(V) \tag{3.13}$$

$$Pn(d_p) = \exp(-(q(d_p)\Delta P) \tag{3.14}$$

Both S and $q(d_p)$ are characteristics of the particular fabric selected.

Because of the complexity of real fabrics and of the mechanisms leading to particle capture, filtration theory should be used as a guide to interpolation, extrapolation, and interpretation of filter data, but not for design de novo. A useful monograph on filtration is that by Davies (1973), and an example of the degree of agreement of theory and experiment was presented by Magee et al. (1975), among many in the literature. Thus, we believe our analysis is useful, but it must be used with caution.

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SECTION 4

IMPLICATIONS

POTENTIAL APPLICATION

The inexpensive commercial face mask we tested, or other such masks, could be donned during an emergency by those living in the vicinity of the reactor and could be used by rescue personnel entering regions of excessive airborne radioactivity. Such masks could be worn for hours without substantial discomfort.

Towels, sheet material, handkerchiefs, etc., could be tied or taped to the face (or held on with "nylon" stockings or panty hose placed over the head and face (Martin, 1981)) for shorter periods during the passage of a puff or plume, during travel to shelter, or during relocation.

These expedients would reduce the inhalation of the airborne radioactive particulates, thus reducing the radiation dose. Our tests also indicate that Kr gas could be delayed by the materials and that I_2 could be reduced substantially by wetted fabrics, but that CH_3I might be virtually unaffected.

POTENTIAL EFFECTIVENESS

The material in the foregoing sections allows one to estimate the effectiveness of some expedient respiratory protection options. To show what this might mean in practice, we have estimated the penetration (fraction avoiding capture) expected through the material (to which would be added some leakage around the seal of the material to the face) for a mask made of 100 cm^2 of the material (an 11-cm-diameter circle or an 8-cm-by-12-cm rectangle, for example) used by someone breathing at the typical adult rate of 10 liters per minute. This would give a ratio of the volume rate of flow to the cloth face area of 1.7 cm/s, close to the 1.5 cm/s value we used in testing the materials and in preparing Table 4.1.

Table 4.1 gives (for dry conditions, then for wet conditions) the material, the approximate number of layers corresponding to 50 Pa (0.2 inches of water) pressure drop, penetrations for aerosols of 0.4, 1, and 5 μm diameter (aerodynamic diameter would be most appropriate, generally) and for CH_3I and I_2 vapors. The aerosol penetrations were estimated from the quality factors using 50 Pa. (A pressure drop of 50 Pa was chosen because it gave values for the number of thicknesses which seemed more practical than did 100 Pa.) The vapor penetrations were taken as the same as at 1 cm/s, but modified by the number of layers of fabric, assuming penetration to be the same for each layer in series, making total penetration the product of the single-layer penetration.

From Table 4.1, it is evident that a double-thickness respirator mask could produce reductions greater than a factor of ten for the aerosol diameters considered, and that the wetted, higher-quality towel could

TABLE 4.1 ESTIMATED PENETRATION THROUGH EXPEDIENT RESPIRATORY PROTECTION MATERIALS AT 50 Pa (0.2 IN H_2O) PRESSURE DROP AND 1.5 CM/S FACE VELOCITY

DRY

Material	No. layers	Aerosol particle diameter (μm)			I_2[b]	CH_3I[b]
		0.4	1	5		
3M respirator[a] # 8710	2	.03	.004	<.01		
Sheet	20	.66	.64	.020	1.0	0.6[c]
Shirt	15	.54	.59	.070		
Lower-quality towel	20	.53	.41	.015		
Higher-quality towel	6	.24	.13	<.01		0.6[c]
Handkerchief	14	.61	.54	.032		

WET

Material	No. layers	Aerosol particle diameter (μm)			I_2[b]	CH_3I[b]
		0.4	1	5		
Sheet	6	.91	.88	.22	.45 .15[d]	.8[c] 1.0[d]
Shirt	6	1.0	.51	<.02		
Higher-quality towel	4	.20	<.01	<.01	.21 .10[d]	1.0
Handkerchief	2	.98	.95	.37		

a. Available commercially in single-layer thickness.
b. Taken from tests at 1.0 cm/s, assuming penetration is the product of single-layer penetrations.
c. Not shown to be statistically different from 1.00.
d. Wetted with 5% by weight baking soda solution.

produce reductions of factors of five or greater for these particle sizes and for I_2.

SECTION 5

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APPENDIX A

CLOTH FILTRATION MODEL

On the pages that follow are reproduced the computer program, discussed in the body of the report, that predicts aerosol penetration (and pressure drop) for cloth fabrics. The model is based on the behavior of isolated cylinders (for the yarns and fibers) and gives some insight into the behavior of cloth filters, but its predictions have not been tested against the results of controlled experiments for cloths. While it should be useful for comparing two cloth designs, for example, the absolute (as opposed to the relative) results of such modeling should not be relied on in designing respiratory protection.

```
C MAIN PROGRAM
      DIMENSION DP(10),DC(3),TAU(10),DIFCO(10)
      DIMENSION EIMP(3,10),EINT(3,10),EDIF(3,10),EGRAV(3,10)
      DIMENSION ESUM(3,10),EMAX(3,10),PNS(10),PNM(10)
      DIMENSION FLENGTH(3),FNUMBER(3),FAREA(3)
      DIMENSION REF(3)
      DATA FAREA/0.5,0.5,.05/

      DATA DC/1.E-4,2.E-4,1.E-5/
      DATA FLENGTH/5000.,2500.,5000./
      DATA NFIBER/3/

      DATA DP/1.0E-9, 1.0E-8, 1.0E-7, 2.0E-7, 5.0E-7,
     + 1.0E-6, 2.0E-6, 5.0E-6, 1.0E-5, 3.0E-5/
      DATA TAU/6.66E-10, 6.82E-9, 8.80E-8, 2.30E-7, 1.02E-6,
     + 3.57E-6, 1.33E-5, 7.93E-5, 3.12E-4, 4.93E-3/
      DATA DIFCO/5.11E-6, 5.23E-8, 6.75E-10, 2.20E-10,
     + 6.26E-11,
     + 2.74E-11, 1.27E-11, 4.86E-12, 2.39E-12, 5.91E-13/

C THESE VALUES ARE FROM THE TABLES BY BGI,INC. FOR NTP

      DATA UFACE/0.2/
      DATA UINF/0.1/

      TYPE 1001

      DO 10 J=1,10
      TYPE 1030, DP(J), TAU(J), DIFCO(J)
10    CONTINUE
      CALL DRAG(NFIBER,DC,UFACE,FAREA,FORCES,REF)
      CALL IMPN(NFIBER,TAU,UFACE,DC,EIMP)
20    CONTINUE
      CALL INTN(REF,NFIBER,DP,DC,EINT)
30    CONTINUE
      CALL DIFFN(NFIBER,DIFCO,UFACE,DC,EDIF)
40    CONTINUE
      CALL GRAVN(NFIBER,UFACE,TAU,EGRAV)
50    CONTINUE
C     END OF SUBROUTINE CALLING FOR SINGLE FIBER EFFICIENCIES
C     PRINT PARTICLE SIZE AND EFFICIENCIES FOR FIBERS
      TYPE 1002
      DO 60 I=1,NFIBER
      TYPE 1004
      DO 60 J=1,10
      WRITE(10,1050), DP(J),EIMP(I,J),EINT(I,J),EDIF(I,J),EGRAV(I,J)
      TYPE 1050, DP(J),EIMP(I,J), EINT(I,J), EDIF(I,J), EGRAV(I,J)
60    CONTINUE
      TYPE 1100
C MAIN PROGRAM CALLS VARIOUS SUBROUTINES AND PRINTS RESULTS
      CALL EFFC(NFIBER,EIMP,EINT,EDIF,EGRAV,ESUM,EMAX)
      CALL PN(NFIBER,ESUM,EMAX,FAREA,PNS,PNM)
      DO 70 J=1,10
      WRITE(11,1030),DP(J),PNS(J),PNM(J)
70    CONTINUE
      TYPE 1110
```

```
      TYPE 1010,FORCES
      STOP
1001  FORMAT(1X,' PARTICLE DIAM  RELAXN TIME   DIFFN COEF ')
1002  FORMAT('SINGLE COLLECTOR COLLECTION EFFICIENCIES')
1004  FORMAT(1X)
1010  FORMAT(1E14.3)
1030  FORMAT(3E14.3)
1050  FORMAT(5E14.3)
1100  FORMAT('THESE ARE DP(J),EIMP,EINT,EDIF,EGRAV FOR SINGLES')
1110  FORMAT('DRAG FORCES, SUMMED')
      END


      SUBROUTINE IMPN(NFIBER,TAU,UFACE,DC,EIMP)
      DIMENSION TAU(10),DC(3),EIMP(3,10)
      DO 100 I=1,NFIBER
      DO 100 J=1,10
      PSI=TAU(J)*UFACE/DC(I)
      IF(PSI.LE.0.8) PSI=0.8
      EIMP(I,J)=1.0 - 0.80/PSI
100   CONTINUE
      RETURN
      END

      SUBROUTINE INTN(REF,NFIBER,DP,DC,EINT)
      DIMENSION REF(3)
      DIMENSION DP(10),DC(3),EINT(3,10)
      DO 100 I=1,NFIBER
      IF(REF(I).LT.1.0)GO TO 50
      DO 10 J=1,10
      X=DP(J)/DC(I)
      EINT(I,J)=(1.+X)-(1./(1.+X))
10    CONTINUE
C     THIS IS POTENTIAL FLOW APPROXIMATION
      GO TO 100
50    CONTINUE
      DO 100 J=1,10
      EINT(I,J)=((DP(J)/DC(I))**2.)/(2.00-ALOG(REF))
C     THIS IS VISCOUS FLOW APPROXIMATION
100   CONTINUE
      RETURN
      END

      SUBROUTINE DIFFN(NFIBER,DIFCO,UFACE,DC,EDIF)
      DIMENSION DC(3),DIFCO(10),EDIF(3,10)
      DO 100 I=1,NFIBER
      DO 100 J=1,10
      PE=DC(I)*UFACE/DIFCO(J)
      EDIF(I,J)=2.7/PE**(0.667)
100   CONTINUE
      RETURN
      END


      SUBROUTINE GRAVN(NFIBER,UFACE,TAU,EGRAV)
      DIMENSION TAU(10),EGRAV(3,10)
```

```
      DO 100 I=1,NFIBER
      DO 100 J=1,10
      G=9.8*TAU(J)/UFACE
      EGRAV(I,J)=G/SQRT(1.0 + G**2)
100   CONTINUE
      RETURN
      END


      SUBROUTINE EFFC(NFIBER,EIMP,EINT,EDIF,EGRAV,ESUM,EMAX)
      DIMENSION EIMP(3,10),EINT(3,10),EDIF(3,10),EGRAV(3,10)
      DIMENSION ESUM(3,10)
      DIMENSION EMAX(3,10)
      DO 100 I=1,NFIBER
      DO 100 J=1,10
      ESUM(I,J)=EIMP(I,J)+EINT(I,J)+EDIF(I,J)+EGRAV(I,J)
      EMAX(I,J)=AMAX1(EIMP(I,J),EINT(I,J),EDIF(I,J),EGRAV(I,J))
100   CONTINUE
      RETURN
      END
C THIS CALCULATES SINGLE COLLECTOR EFFICIENCY TWO WAYS
C ESUM IS THE SUM OF THE INDIVIDUAL MECHANISMS
C EMAX IS THE MAX OF THE INDIVIDUAL MECHANISMS


      SUBROUTINE PN(NFIBER,ESUM,EMAX,FAREA,PNS,PNM)
C THIS SUBROUTINE COMBINES THE EFFICIENCIES FOR THE COLLECTORS
      DIMENSION ESUM(3,10),EMAX(3,10),FAREA(3),PNS(10),PNM(10)
C     INITIALIZE
      ZERO=0.0
      DO 90 J=1,10
      PNS(J)=1.0
      PNM(J)=1.0
90    CONTINUE
C     CALCULATE PENETRATIONS BOTH WAYS
      DO 100 J=1,10
      DO 100 I=1,NFIBER
      PNS(J)=PNS(J)*(1.0-ESUM(I,J)*FAREA(I))
      PNM(J)=PNM(J)*(1.0-EMAX(I,J)*FAREA(I))
      PNS(J)=AMAX1(ZERO,PNS(J))
      PNM(J)=AMAX1(ZERO,PNM(J))
100   CONTINUE
      RETURN
      END


      SUBROUTINE DRAG(NFIBER,DC,UFACE,FAREA,FORCES,REF)
      DIMENSION DC(3),FAREA(3),FORCE(3)
      DIMENSION REF(3)

C     CONSTANTS FOR AIR AT 25 C AND 1 ATM
C     DENSITY
      DENS=1.18
C     VISCOSITY
      VISC=1.83E-5
      DO 1000 I=1,NFIBER
```

```
C       REYNOLDS NUMBER
        REF(I)=DENS*UFACE*DC(I)/VISC
C       FLOW RESISTANCE COEFFICIENT
        CDPRM=9.689*REF(I)**(-0.78)

        IF(REF(I).LT.0.1)GO TO 15
        IF(REF(I).LT.5.0)GO TO 20
        IF(REF(I).GT.40.0)GO TO 30
C       REF BETWEEN 5 AND 40
10      CD=CDPRM*(1.0+0.227*(REF(I)**0.55))
        GO TO 100
C       REF LESS THAN 0.1, USE LAMB
15      CD=8.0*3.1416/(REF(I)*(2.002-ALOG(REF(I))))
        GO TO 100
C       REF BETWEEN 0.1 AND 5
20      CD=CDPRM*(1.0+ 0.147*REF(I)**0.82)
        GO TO 100
C       REF BETWEEN 40 AND 400
30      CONTINUE
        CD=CDPRM*(1.0+0.0838*REF(I)**0.82)
        GO TO 100
C       EXCEPT FOR LAMB FORMULA, THESE FROM CLIFT ET AL.
100     TYPE 1101
        TYPE 1102, REF(I),CD
C       FORCES WITHOUT POROSITY CORRECTIONS
C       FORCES (NEWTONS) EQUAL PRESSSURE (N/M**2)

1000    FORCE(I)=CD*FAREA(I)*0.5*DENS*UFACE**2.
        FORCES=FORCE(1)+FORCE(2)+FORCE(3)
        TYPE 1103
        TYPE 1104, FORCE(1),FORCE(2),FORCE(3)
1101    FORMAT('REYNOLDS NUMBER, DRAG COEF')
1102    FORMAT(2E14.3)
1103    FORMAT('FORCES FROM EACH FIBER TYPE')
1104    FORMAT(3E14.3)
        RETURN
        END
```

```
C                NOMENCLATURE

C DIFCO IS THE PARTICLE DIFFUSION COEFFICIENT,M**2/S
C DP IS THE PARTICLE GEOMETRIC DIAMETER, M
C EDIF IS THE CYLINDER COLLECTION EFFICIENCY
C EGRAV IS THE CYLINDER GRAVITATIONAL COLLECTION EFFICIENCY
C EIMP IS THE CYLINDER IMPACTION COLLECTION EFFICIENCY
C EINT IS THE CYLINDER INTERCEPTION COLLECTION EFFICIENCY
C EMAX IS THE LARGEST OF THE CYLINDER COLLECTION EFFICIENCIES
C ESUM IS THE SUM OF THE CYLINDER COLLECTION EFFICIENCIES
C FAREA IS THE FRACTION OF THE CROSS-SECTIONAL AREA
C       OCCUPIED BY THE PARTICULAR FIBER TYPE
C FLENGTH IS THE LENGTH OF A PARTICULAR FIBER TYPE IN ONE M**2
C FNUMBER IS THE NUMBER OF A PARTICULAR FIBER TYPE IN ONE M
C NFIBER INDICATES WHICH FIBER TYPE
C PE IS THE PECLET NUMBER
C PN IS THE PENETRATION
C PNM IS THE PENETRATION OF A FIBER TYPE LAYER, BASED ON EMAX

C PNS IS THE PENETRATION OF A FIBER TYPE LAYER, BASED ON ESUM
C REF IS FIBER REYNOLDS NUMBER
C TAU IS THE AEROSOL PARTICLE CHARACTERISTIC AERODYNAMIC TIME
C UFACE IS THE FACE VELOCITY, CORRECTED FOR FRACTIONAL OPEN AREA
C UINF IS THE FACE VELOCITY, UNCORRECTED
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